port No. FHWA-RD-75-33

ASIBILITY OF UTILIZING HIGHWAY BRIDGES TO WEIGH VEHICLES IN MOTION

Vol. I. Exotic Sensors on the Bridge Deck

J. W. Fothergill, H. D. Childers, and M. A. Johnson

November 1974
Final Report

This document is available to the public
through the National Technical Information
Service, Springfield, Virginia 22161

Prepared for

FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. 20590

FHWA DISTRIBUTION NOTICE

Limited copies of this report are being distributed by memorandum to researchers and others directly concerned with the results of the feasibility study.

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-RD-75-33		

4. Title and Subtitle	5. Report Date
FEASIBILITY OF UTILIZING HIGHWAY BRIDGES TO WEIGH VEHICLES IN MOTION. Exotic Sensors on the Bridge Deck	November 1974
	6. Performing Organization Code
7. Author(s): J. W. Fothergill, H. D. Childers & M. A. Johnson	8. Performing Organization Report No.
9. Performing Organization Name and Address: Integrated Systems, Inc. (a Maryland corporation) 11880 Coakley Circle Rockville, Maryland 20852	10. Work Unit No. (TRAIS): FCP-35F4-052
	11. Contract or Grant No.: DOT-FH-11-8471
12. Sponsoring Agency Name and Address: Offices of Research and Development Federal Highway Administration Department of Transportation Washington, D. C. 20590	13. Type of Report and Period Covered: Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

FHWA Contract Manager H. R. Bosch (HRS-11)

16. Abstract

The object of this study was to determine the feasibility of utilizing highway bridges to weigh vehicles in motion. Specifically, the study was to determine the feasibility of developing a total system to acquire, record, and reduce in-motion collected vehicle data, comprising dynamic axle load, dynamic truck load, static axle weight, vehicle weight, number of axles, axle spacing, headway, truck lane of occupancy, truck type, and truck arrival time.

Two forms of dynamic load sensors were investigated, direct-contact form which would sense directly from tire contact, and indirect forms, which measured a resultant bridge behavior effect. A total of nine forms of direct-contact transducers was identified which could be produced in one or both of two geometric designs which were developed. Of the indirect sensors, only seimic were investigated in depth. The study was constrained contractually from considering the classic strain gage approach

Study results indicated that a significant test and evaluation effort was necessary before a firm decision could be made on the practicality of using seismic sensors. All of the information collected on the use of seismic sensors was very favorable, but not sufficiently conclusive to commit to the fabrication of a sensor system.

This report is the first in a series. The others in the series are:
FHWA No. 75-34, Short Title: Strain Gages on Main Longitudinal Members
FHWA No. 75-35, Short Title: Strain Gages at Bridge Bearings

17. Key Words	18. Distribution Statement
Bridges, Sensors, Weighing, in motion, dynamic loads, trucks, seismic sensing, vehicle detection	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	256	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENTS

During the Literature Survey portion of this study, considreable assistance was received from Mr. David Ewing, Supervising Retrieval Specialist, Transportation Research Board, and Miss Mary Jo Burke at the Department of Transportation library.

Mr. Ewing's assistance in the use of the HRIS facility, and in delimiting the list of keywords used in the HRIS searches, helped to make the searches efficient, thorough, and relevant. The two HRIS searches performed by Mr. Ewing proved to be the most useful searches made during the retrieval portion of the Literature Survey.

Miss Burke's cooperation and help made the retrieval of documents at the DOT library as efficient and relevant as posible. Without her help, the document retrieval portion of the Literature Survey would have taken far longer to accomplish.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
BACKGROUND	3
LITERATURE SURVEY	9
DOCUMENT RETRIEVAL	9
REVIEW OF DOCUMENTS	13
DATA ACQUISITION AND RECORDING	14
IN-MOTION WEIGHING REQUIREMENTS	18
Passage Time	32
Array Design	34
FUNCTIONAL REQUIREMENTS	44
Acquisition System Design Characteristics	46
Acquisition System Design Constraints	49
LISTING AND DESCRIPTION OF LOAD SENSORS	52
LOAD SENSORS	52
Pneumatic-Hydraulic	60
Electronic Scales	61
Magnetostrictive (Triboelectric) Transducers	61
Peizoelectric Crystals	70
In-Series Load Cell	73
Exotic Elastomer and Plastics	77
Conductomer	78
Silicone Rubber	82
Capacitance Sensor	83
Indirect Load Sensors	86
INSTALLATION CONSIDERATIONS	100
SUPPORTING SENSORS	103
Chemical Sensors	105
Optical	105
Acoustic Sensing	105
Video	107
Laser Radar	108
Ultrasonic Sensors	108

TABLE OF CONTENTS (Continued)

	Page
Induction Loops	109
Magnetic Transducers	109
Radar	110
COMPARATIVE ANALYSIS OF SENSING SYSTEMS	111
Load Sensors	111
Support Sensors (PVD)	115
DEFINITION OF ACQUISITION SYSTEM	118
DIRECT FORM LOAD TRANSDUCER DESIGN	120
Capacitor Weight Sensor	121
Capacity Pad Electronics	127
Axle Count Processor	129
PROPOSED PASSAGE AND VELOCITY DETECTOR (PVD)	133
RF Section	134
Processor	137
Mechanical Construction	141
LANAL PROCESSING PACKAGE	141
WEIGHT SENSOR PROCESSOR	145
BRIDGE PROCESSOR PACKAGE	150
DATA REDUCTION AND INTERPRETATION	153
REQUIREMENTS	153
DATA REDUCTION DESIGN CONSIDERATIONS	159
REDUCTION PROCESS	160
Vehicle Classification	169
CONCLUSIONS AND RECOMMENDATIONS	177
CONCLUSIONS	177
RECOMMENDATIONS	180
REFERENCES	182
APPENDIX A - KEYWORD LIST FOR AUTOMATED SEARCHES	188
APPENDIX B - SELECTED BIBLIOGRAPHY	196
APPENDIX C - DETERMINATION OF BRIDGE COMPONENTS	218
APPENDIX D - CONCEPTUAL SEISMIC SENSOR SYSTEM	226

LIST OF ILLUSTRATIONS

Figure No.		Page
1.	Driving Functions in Dynamic Loads	21
2.	Scope of University of Texas Study	26
3.	Vehicle - Road Interaction	27
4.	International Tractor and Freuhauf Trailer	35
5.	Typical Cyclic Period for 50 mph @ 3 cps	37
6.	Theoretical Damping	38
7.	Position of Sensors on Bridge	41
8.	Basic Magnetostrictive Transducer	65
9.	Cross-Section of Magnetostrictive Transducer	66
10.	Longitudinal Section of Magnetostrictive Transducer	67
11.	Installation of the Magnetostrictive Transducer	68
12.	Example of Multiple Compressive Sensor Deck Installation	69
13.	Piezoelectric Transducer	72
14.	Cord Load Transducer	75
15.	In-Series Load Cell	76
16.	Conductomer Transducer - Type I	80
17.	Levelmeter Recording Along an Expressway	93
18.	Standard Embedded Sensor Package	122

LIST OF ILLUSTRATIONS (Continued)

Figure No.		Page
19.	Layered Capacitor.	124
20.	Silicone Rubber Insulator.	124
21.	Capacity Pad Electronics	128
22.	Oscillator Excitation Frequency.	130
23.	Axle Count Processor	131
24.	Pulse Sequence for Axle Count.	132
25.	Doppler Radar-RF Portion	135
26.	Doppler/Passage Pulse Sensing.	138
27.	Doppler Processor.	139
28.	Lane Package Block Diagram	142
29.	Lane Programmer...	144
30.	Data Format.	146
31.	Weight Sensing Processor Block Diagram	148
32.	Pulse Timing for Weight Sensor	149
33.	Bridge Processor Package (BBP)	151
34.	Data Reduction Process	161
35.	Example of Classification Subroutine Flow	172
36.	Seismic Data Reduction Process	225
37.	Comparison of Predicted and Measured Signal Characteristics	245

LIST OF TABLES

Table No.		Page
1.	Standard 3S2 Truck "TBE".	33
2.	Period Spacing (Fast)	36
3.	Basic Sensor List	53
4.	Candidate Sensors	57
5.	Relative Broad Band Amplitudes.	95
6.	Load Sensor Camparisons	112
7.	Candidate Support Sensor (PVD) Comparison.	116
8.	Truck Classification Tabulation	170

LIST OF SYMBOLS

$f_{AX_k}(t)$	=	Dynamic load function of the k^{th} axle of a vehicle
$g[f_{AX_k}(t)]$	=	Operator which converts a given dynamic axle load to a static axle weight
i	=	Computational loop index
K	=	Number of axles determined in the data-reduction process
k	=	Axle being processed
N_{AX}	=	Recorded number of axles from the acquisition system
N_{DYN}	=	10,000-lb (4,536-kg) dynamic axle load threshold switch, $N_{DYN} = 0$ implies the dynamic axle load < 10,000 lb (4,536-kg) $N_{DYN} \neq 0$ implies that the static axle load $\geq$ 10,000 lb (4,536 kg)
t	=	Time, sec
t_{AX_k}	=	Arrival time of the k^{th} axle of the vehicle being processed
t_H	=	Headway reference time
V	=	Vehicle speed sensed by the PVD and recorded by the on-site processor
W_{SAX_k}	=	Static axle weight (lb) (.4536-kg) of the k^{th} axle of the vehicle being processed
Δt_H	=	Headway time between the previous vehicle and the vehicle being processed
ΔX_k	=	Space between the k and k+1 axles of a given vehicle

INTRODUCTION

The work performed and the results achieved under Contract FH-11-8471 to the Federal Highway Administration (FHWA), Structures and Applied Mechanics Division, for "Determining the Feasibility of Utilizing Highway Bridges to Weigh Vehicles in Motion," is described within this report.

The contractual objective of this study was to: "Determine the feasibility of utilizing steel girders with concrete slab highway bridges for weighing trucks, obtaining dynamic loads, and evaluating truck traffic conditions." More specifically, it was to determine the feasibility of developing a total system to acquire, record, and reduce in-motion collected vehicle data, such as dynamic axle weight, speed, number of axles, axle spacing, headway, lane of occupancy, truck type, arrival time, and static axle and vehicle weights.

The specific contract requirements were that: "This study will investigate the feasibility of utilizing a sensor measurement system on highway bridges as a basis for weighing trucks, obtaining dynamic loads, and evaluating truck traffic conditions. For each truck crossing the bridge with axle weights of more than two thousand pounds, the following information shall be obtained:

1. Truck type

2. Arrival time

3. Headway

4. Truck velocity

5. Bridge lane occupancy

6. Truck gross weight (over 10,000 lb)

7. Individual axle weight (over 10,000 lb)

8. Axle spacing and number of axles per vehicle

9. Dynamic loads for vehicles with axle weights over 10,000 lb."

The above requirements were, in essence, performance requirements. They in no way defined the functional requirements of the system.

This study was one of three independently conducted studies which all had the same end objective of "weighing vehicles in-motion" on a bridge deck. However, this study was constrained from considering the classical approach of abstracting vehicle weight from bridge beam bending moments, i.e., using beam-mounted strain gages. Although three independent studies were conducted to evaluate the feasibility of "in-motion" weighing using bridge decks, each study was oriented toward a different approach. This study was primarily concerned with the potential use of exotic forms of sensors, e.g., military and law enforcement intrusion detectors, pressure-sensitive elastomers, and thin-film plastics.

BACKGROUND

A large number of surveys and studies have been performed over the past 20 years to collect static truck weights and truck type data on highways and, correlated with stress studies, on bridges. These studies also usually provided truck type incidence statistics and, to some extent, temporal distributions. Such studies and surveys were usually of a one-shot form and of short duration, which implies small samples in the time domain and the total population. At present, such surveys and studies form the empirical basis for long-term bridge loading predictions. The use of such small samples leads to a significant uncertainty in the representation of the current population and in the prediction of long-term populations. These surveys and studies are further limited to certain highways and bridges with loadometer stations available nearby. Consequently, the truck loading endured by many bridges can only be hypothesized on the basis of very weak statistical data.

In addition to the lack or representation data, there are significant deficiencies in the kind of data that has been collected in the past. Although loadometer stations can and do provide static gross vehicle weight and static gross axle weight, there is presently no practical means of relating such data to the actual dynamic axle loads which any given truck will impose on any given bridge deck, with the exception of bridge strain measurements. Further, little data is available on the platooning behavior, lanal behavior, speed, and headway of trucks on bridge decks.

In order to collect data of the form discussed above, presently and in the past, it has been necessary to use human observers with rather crude techniques and instrumentation. The use of human observers and loadometer stations cannot help but modify the population being sampled and, hence, skew the sample, e.g., toward lighter-than-normal loadings.

These considerations begin to define the need for an automatic, inconspicuous, "in-motion" dynamic weighing system for use on bridges. In a general manner, the above considerations imply the need for a system capable of:

1. Collecting, recording, and reducing truck traffic data which will provide the following reduced data:

    a. Truck type

    b. Arrival time

    c. Headway

    d. Truck speed

    e. Lane of occupancy

    f. Gross static weight

    g. Axle static weight

    h. Axle spacing and number

    i. Gross vehicle and axle dynamic load

2. Being used without modification of the bridge structure

3. Measuring all of the necessary variables in an "in-motion" manner

4. Causing no perturbation in the normal traffic behavior and, particularly, in the normal dynamic loading functions.

Given the data in 1 above, a great deal can be deduced concerning the characteristics of the truck population which uses a given bridge, e.g.:

1. Depending on the sampling form of the "in-motion" dynamic weighing sensor, estimates of each truck's dynamic load function, as imposed on the deck, can be determined;

2. The dynamic range, then, can also be estimated;

3. The classic dynamic load factor, or, perhaps more accurately, the dynamic load transfer function, can be determined more realistically and more accurately for any given bridge;

4. Characterization can be made of truck platoons, platoon behavior, and platoon statistics on bridge decks.

As a result of such considerations and needs, the FHWA contracted for the performance of investigations into the feasibility of developing a "sensor measurement system." The

contractually required work for this particular study was defined as follows: The contractor shall, as a minimum, accomplish the following tasks in meeting the objective of this contract:

1. Task A - Literature Survey - Conduct a literature survey emphasizing identification, definition, and assessment of new, improved, or untried sensors in this field capable of acquiring the data necessary for determining items a-i of 1 above. This survey will include a study of on-going or recently completed research projects to identify sensors that appear to have merit and to develop ranges of parameters that may be expected.

2. Task B - Data Acquisition and Recording - Conduct the following subtasks using the results of Task A to:

   a. Establish desirable requirements for the instrumentation system necessary to monitor and record the data for obtaining items a-i of 1 above

   b. Develop a listing and description of the sensors capable of acquiring data that either directly or indirectly contain data items a-i. Identify any other truck traffic variables which would be of value in predicting the behavior and content of vehicle loads

c. Determine and catalogue characterisitcs of each of these sensors, e.g., manner of installation, sensitivity, response, power needs, reliability, and cost

d. Define single-sensor or multi-sensor acquisition systems to satisfy the requirements

e. Develop a definition of the structure and components contents of each candidate system

f. Make a comparative analysis of the characteristics of each candidate instrument system versus both the desirable and minimum system requirements, including a comparison of operation, maintenance, cost, and constraining factors.

3. Task C - Data Reduction and Interpretation - Conduct the following subtasks using the data acquired in Task B:

    a. Analyze and evaluate candidate systems for time signal synchronization and multi-channel recording and reduction

    b. Establish the feasibility of reducing the acquired data to the required data elements as an end product

    c. Present a detailed description of the solution algorithm.

The basic approach to this investigation will be to obtain vehicle weights and vehicular data from techniques other than that of abstracting the data from bridge beam bending moments.

LITERATURE SURVEY

DOCUMENT RETRIEVAL

The first task of this study was to conduct a literature survey in order to identify and assess related studies either completed or on-going. The first step within this task was to identify possible sources of this data. The primary consideration in the selection of these sources, due to the short time-frame of this project, was to determine from which sources the most data could be retrieved in the shortest possible time. At the start of the contract, a project meeting was held, and the following list of sources of information was compiled:

1. Transportation Research Board (TRB)*

2. Department of Transportation (DOT)

3. Smithsonian Institution*

4. Federal Aviation Administration (FAA)

5. National Aeronautics and Space Administration (NASA)*

6. National Bureau of Standards (NBS)*

7. National Technical Information Service (NTIS)*

8. American Trucking Association

9. National Cooperative Highway Research Program (NCHRP)

10. National Highway Traffic Safety Administration (NHTSA)

11. Society of Automotive Engineers

12. Defense Documentation Center (DDC)

13. Tire Manufacturers

14. American Association of State Highway Officials (AASHO)

15. Ft. Belvoir/Ft. Monmouth/other military installations.

It was determined that some of these organizations had an automatic search capability (*) and that these should be the first organizations to be contacted.

A keyword list with delimiting conditions was constructed to form the basis of the computerized abstract file searches. Care was taken to prevent the retrieval of excessive quantities of abstracts by delimiting the queries.

Initial contact was made with TRB. It was determined that all relevant information from all of the above-mentioned agencies and organizations except NASA, NTIS, DDC, and Ft. Belvoir/Ft. Monmouth/other military installations was included in the HRIS files at TRB. After several discussions with TRB, it was determined that further delimiters would have to be added to the list of keywords to be used in the HRIS search in order to avoid a retrieval so large as to be unmanageable. This list of keywords is included as Appendix

A to this report. Because of the amount of valuable information contained in the HRIS files, two searches were necessitated, even after the keyword list had been delimited.

However, the searches of the HRIS files were meaningful and thorough and resulted in a retrieval of 2,745 abstracts. After a thorough review of these abstracts, 478 were selected that appeared relevant to the project.

At the same time that the HRIS search was being performed at TRB, contact was made with NTIS and NASA in order to initiate a search of their files. It was determined that the material available from the various military installations is available from DDC, and the DDC information is contained in the NTIS files. Further delimiters were added to the NTIS search in order to avoid duplication of material retrieved at TRB and to ensure that only unclassified material would be retrieved from the search. The search at NTIS produced 322 abstracts, 69 of which appeared relevant to the project.

After several contacts with NASA, it was determined that NASA would not allow a search of their files to anyone not under contract to them. Although part-way through the project ISI came under contract to NASA, the two projects were on completely unrelated subjects, and, therefore, NASA would still not allow a search.

After the abstracts retrieved were reviewed and those abstracts which appeared relevant were selected, retrieval of the documents was begun. The library at DOT was determined to be the logical place to begin. Initially, it was felt that a few days in this library would be sufficient to

retrieve all the documents that they might have. However, the library is so large and contains documents from so many sources, that it was soon obvious that this would be the main source of documents and that it would take considerable time to retrieve everything available there. An arrangement was made with the library whereby a large amount of documents could be borrowed from the library for several days to be reviewed. This meant that while one group of documents was being reviewed, another group could be be searched for and retrieved. This made retrieval far simpler and saved considerable time in the retrieval of these documents. A total of 478 documents that were identified by the HRIS searches were searched for at this library. Of these, 384 were retrieved. Of those retrieved, 75 were duplicates, 6 were too old to be of value, 80 were not relevant to the project, and 3 were in foreign languages, leaving a total of 220 relevant documents retrieved and reviewed from this one source.

The 69 relevant documents identified in the NTIS search were ordered from NTIS, the Government Printing Office, and the Patent Office and were reviewed upon their receipt.

In addition to the retrieval of the documents identified in the HRIS and NTIS searches, specific manual retrievals were made on the basis of the identification of individual researchers who have worked consistently in the areas of interest, and subject matter areas in the card files at the DOT library. As a result of these searches, an additional 211 documents were retrieved and reviewed.

In addition to the retrieval of unclassified military material identified in the NTIS search, other information concerning on-going military research in related areas of interest was acquired through queries made on a personal level by the investigators to individuals at various military installations.

The 431 relevant documents retrieved as a result of all of the searches covered such a broad spectrum of the areas of research related to this project that it was determined that, given the time contraints imposed by the contract, no further searches for documents from other sources would be initiated. Many of the documents which were identified from the abstracts, but which were not available from the DOT library, from NTIS, or from other Government sources, were foreign. The difficulty of acquiring foreign research information has largely been supplanted by the excessive quantity of data. No critical foreign research document was identified which is published in English but not available through one of the above-mentioned sources. No attempt at translating non-English documents was attempted because of schedule requirements and the quantity of available documents published in English.

REVIEW OF DOCUMENTS

In order to review the enormous quantity of retrieved documents in the most expeditious manner, the investigators sorted the documents by subject area:

1. Sensor data

   a. Military and law enforcement intrusion sensors

b. Traffic and highway sensors

c. In-motion weighing systems

d. Strain gages

e. Non-destructive testing of material

f. Transducers

g. Instrumentation for highway/bridge applications

h. Data reduction and analysis for bridge/highway applications

2. Bridge/highway data

a. Bridge dynamics

b. Concrete seismic characteristics

c. Bridge loading/stresses

3. Vehicle data

a. Truck data; load, classification, lanal distribution, platooning

b. Vehicle dynamics

c. Tire dynamics and characteristics

4. Sealing and bonding agents

5. Other.

After the documents had been sorted into these categories, the investigators determined which categories should have the highest priority for review. The categories were then organized in priority order.

Starting with the documents of highest priority, and working downward, the documents were scanned for meaningful data, and this data was extracted from them in note form. After all of the documents had been scanned, those which appeared to be the most significant were carefully reviewed and abstracted by the investigators.

By following these steps in reviewing the documents, the investigators were able to use to the greatest advantage the vast quantity of information that was retrieved. Also, by using this method of review, a significant amount of redundancy of data was identified and the redundant data deleted, thus further minimizing the abstracting effort.

DATA ACQUISITION AND RECORDING

The first step in determining the system requirements of the acquisition and recording portion of the "sensor measurement system" was to identify the functional requirements of the system from the essential performance requirements which were contractually specified. Defining the functional requirements of the system was not a straightforward matter, since some of the variables to be acquired could be acquired in a multiplicity of manners, and many alternative configurations of acquiring sensors could be developed which would provide the same resulting variables. Further, there were many alternatives available in selecting the variables to be acquired as raw data and those which could be reduced from the raw data. The most pragmatic approach to this problem was to require that the system acquire the minimum set of variables necessary to generate the total set required. This immediately implied the existence of two modes of operation for the system, i.e.:

1. An acquisition and recording mode

2. A reduction mode.

The minimum set of variables which must be obtained for each vehicle crossing a bridge are:

1. Arrival time of the vehicle

2. Lane of occupancy

3. Dynamic load of each axle (wheel)

4. Time of axle sensing

5. Speed of the vehicle.

All other necessary variables can be derived from this minimum set of variables.

Early in the study, it became apparent that a broad investigation of sensors as was done by Texas Instruments (1), General Electric (2), and, undoubtedly, others, would be academically interesting, but would lead nowhere in particular. It also became apparent quite early that no single sensor could furnish all of the variables required. The investigation was directed toward sensors which were capable of acquiring, directly or indirectly, a variable which explicitly or implicitly defined the dynamic axle load of a vehicle moving over a given bridge. The definition of either a static or a dynamic load is force. The factors which enter into and result from force are mass, acceleration, pressure, area, energy, etc. Consequently, if we can sense a factor of the vehicle load input to the bridge deck, or if we can sense a resultant factor from the bridge deck, we can draw some conclusions about the imposed vehicle dynamic load, or, more specifically, the imposed axle dynamic load.

Because the imposed force exhibits itself in this manner, two categories of "in-motion" dynamic load sensor systems were established, i.e.:

1. Direct, which measures a factor of the input dynamic axle load, such as pressure

2. Indirect, which measures a factor of the resultant bridge behavior due to a given dynamic axle load.

Because of the differences in the form of the data acquired by the two different categories, differences will exist in the acquisition and recording subsystem requirements.

IN-MOTION WEIGHING REQUIREMENTS

In order to realistically design an "in-motion" weighing system for a bridge deck, it is first necessary to acquire a full understanding of exactly what is being measured. As all highway and bridge engineers know, "in-motion" weighing does not provide a measure of the axle weight. The resulting measurement of an "in-motion" weighing system is, in fact, a sample of the dynamic axle load, or some manifestation of it, imposed on the bridge deck. Consequently, it becomes extremely important to the developers of an "in-motion" weighing system to fully understand the dynamic load functions which the axles of various vehicles or various surfaces impose on a bridge deck.

After reviewing a large amount of literature on previous "in-motion weighing" systems and investigations of vehicular dynamic load functions, the total orientation of this study was directed toward the concept of sensing the vehicular dynamic load function either in multiple discrete sampling or in a continuous manner across a bridge span. Concern over direct determination of a vehicle's static weight was completely put aside because of the need to determine a valid representation of a truck's dynamic load function. It is

essential that the dynamic load function be determined before an accurate estimate of the static weight can be derived.

Three rather comprehensive dynamic truck load investigations provide a great deal of insight into the problems which a developer of an "in-motion" weighing system must consider:

1. The Philco investigation (3)

2. The General Motors investigation (4)

3. The University of Texas investigation (5).

Previous "in-motion" weighing systems have been largely concerned with determining accurate static weight per axle and for the entire vehicle. As a result, significant effort has been exerted in the design of, as a rule, electronic scales. In some instances, investigators have abandoned their work because of their inability to establish a generalized relationship between their observed weights and the actual static weights of their samples. In many instances, scant attention, if any, was paid to the existence and form of the dynamic load which was, in fact, what these investgators were actually measuring.

High-order accuracy of the static load is of limited value. It is primarily of importance to the enforcement of legal load limits. The use of an "in-motion" approach in this application is justified by its elimination of the very significant delays encountered by truckers from the off-the-road static scales.

However, for this application, the investigators were not as much interested in high-order accuracy of the static weight as in the actual dynamic load being applied to the bridge deck and the manner in which it distributed on the deck.

The investigators were also extremely interested in determining the range of the applied dynamic loads, which is analogous in requirements to the requirements for determining the high-order accuracy of static weight. In order to establish some approximation of the dynamic range, it is necessary in the use of any compressing or direct-wheel-pressure sensor to acquire multiple measurements. These measurements must be taken, ideally, such that they effectively sample the dominant component of the dynamic function for any truck on about a 1/4-cycle basis (Figure 1). A minimum of three measurements would be required to provide an approximation of one cycle of the dynamic function.

However, the variations in truck speeds and the responses of their suspension systems imply that the installation of three such sensors would not be sufficient to characterize the dynamic load functions of all trucks. Hence, more such sensors would be required and would have to be installed in a manner that they could sample adequately over at least 3/4 of the wave length, .75λ, of the dominant mode of all vehicles.

Such an approach is fundamental to the use of pressure-type load sensors of, effectively, the instantaneous sampling variety. The proposed use of long-load sensors imposes difficulties, as were encountered by Philco (3), such as achieving zero effects from the sensor itself. The use of very small instantaneous sensors in a multiple manner along the path of

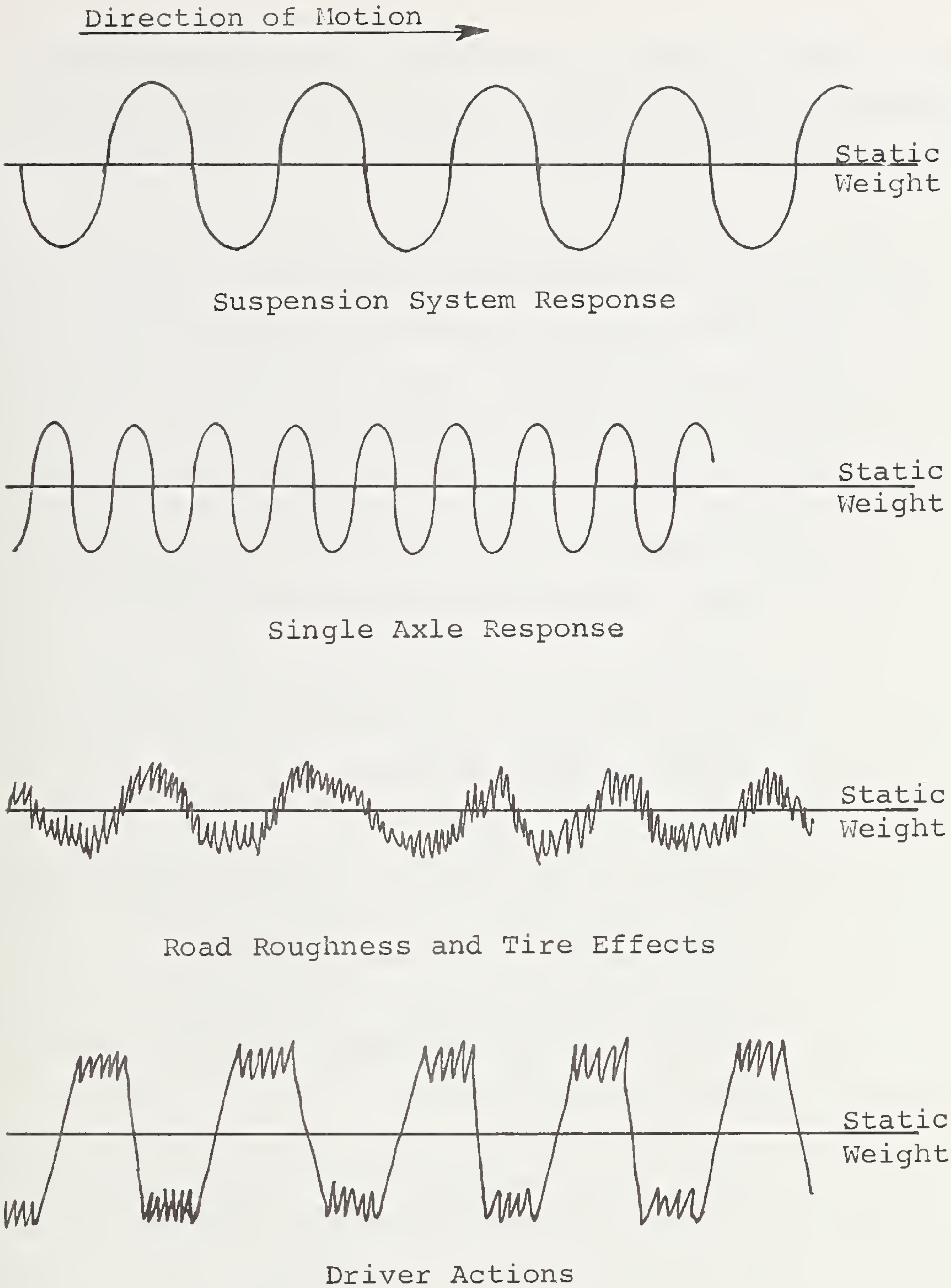


Figure 1. Driving functions in dynamic loads.

a vehicle provides the most direct and effective means of obtaining a characteristic representation of a vehicle's dynamic function over that segment of a road/deck surface.

The use of multiple load sensors of the pressure type is complicated by the surface perturbational effects caused by the sensors themselves. Philco's (3) experimentation indicated that as little as 1/16-inch (.159-cm) variation in a road surface affected the behavior of the resultant dynamic load function. This implies that the introduction of several load sensors in or on the road/deck surface will, in itself, significantly change the measured dynamics of a vehicle from what it was before the installation of the sensors. This would not prohibit the determination of estimates of the true dynamic behavior of a vehicle over this segment of road/deck, but it complicates the problem and imposes more effort in extracting the information desired.

Explanations of the variations of recorded dynamic loads about the static weight included "normal scatter," within the "limits of probable chart reading error," etc. It appears that there was a failure to admit the existence of a sinusoidal dynamic function which was further distorted by higher frequency oscillating functions.

Assumptions about the smoothness of the road surface have undoubtedly created difficulties for other investigators. Evidence of the serious effects of 1/16-inch (.159-cm) variations in the road surface on the observed dynamic load function make the assumption of the existence of a "perfectly level surface" on highways meaningless. Further, such assumptions totally disregard the influence of the driving forces of the

vehicle components on the dynamic load function, such as out-of-round tires which are independent of the road surface and which excite the vehicle suspension system and the individual axles.

In the Philco work (3), dynamic factors of 1.4 were often observed, and factors as large as 1.8 were found on a particularly smooth roadway. Also, tandem axles appeared to be more sensitive to weight shift influence than single axles. They tended to teeter and to provide the largest source of error, -17.6 to +19.1 percent in the measurements made by Philco. However, maximum error for total truck weight was -9.2 and +7.2 percent, with an absolute average of 2.65 percent.

To estimate static weight from multiple, sequential, dynamic measurements, the Philco study hypothesized that:

$$\overline{W}_a = \frac{\Sigma a_i \overline{W}i}{n},$$

$$a_i = F[V_v, V_w, \theta_w, f(\overline{W}_1, \overline{W}_2, \ldots, \overline{W}_n)],$$

where

V_v = vehicle velocity,

V_w = wind velocity,

θ_w = wind direction, and

$f(\overline{W}_1, \overline{W}_2, \ldots, \overline{W}_n)$ = a combination of mean values each observed scale for n scales.

The reported results were only partially successful.

Some of the determinations made in the General Motors study (4) included:

1. That road profile excitation at 10 cps was typically three times greater at 69 mph (109.44 km/hr), [10-ft (3.048-m) wavelength, or .1 cpf (.328 cpm)] than at 34 mph (54.74 km/hr), [5-ft (1.524-m) wavelength, or .2 cpf (.656 cpm)].

2. That most of the trucks surveyed used leaf-spring suspension and were equipped with 10 x 20 bias-ply tires

3. That a step-type bump in the roadway caused the greatest excursion of the dynamic load function

4. That the maximum dynamic load occurred during initial compression of the tire

5. That a step bump contained all frequencies and, hence, showed no preference for a particular speed or other vehicle property

6. That no significant pavement load differences were observed between new and worn bias-ply tires

7. That bias-ply tires caused somewhat greater dynamic pavement loads than radial-ply tires

8. That pavement loads increase with tire pressure

9. That pavement loads increase slightly with vehicle speed (This was also evidenced in other studies.)

10. That power spectral density analysis of pavement load indicated consistent peak frequencies at 3 to 4 cps

11. That the body mode dominated on smooth roads, whereas wheel rotation modes dominated above 8 cps, and body mode and wheel-hop frequencies dominated on rough roads.

The importance of the dynamic load function is clearly evident in the work performed by Al-Rashid, et al. (5). The comprehensiveness of their work is illustrated in Figure 2 and the complexity of the dynamic load function, as considered by them, is illustrated in Figure 3. Dynamic loads were measured up to 250 percent of the static load in this work and, more importantly, were measured on a bridge deck. Three-quarter-inch (1.905-cm) bumps placed 50 inches (127 cm) apart on a bridge deck generated dynamic axle loads of 250 percent of their static weight. Similar conditions can develop in the pavement of a bridge deck. Single 3/4-inch (1.905-cm) bumps generated dynamic loads of 180 percent of the static load.

This work also indicated which factors affected the measured dynamic load, i.e., in the order of importance in descending order:

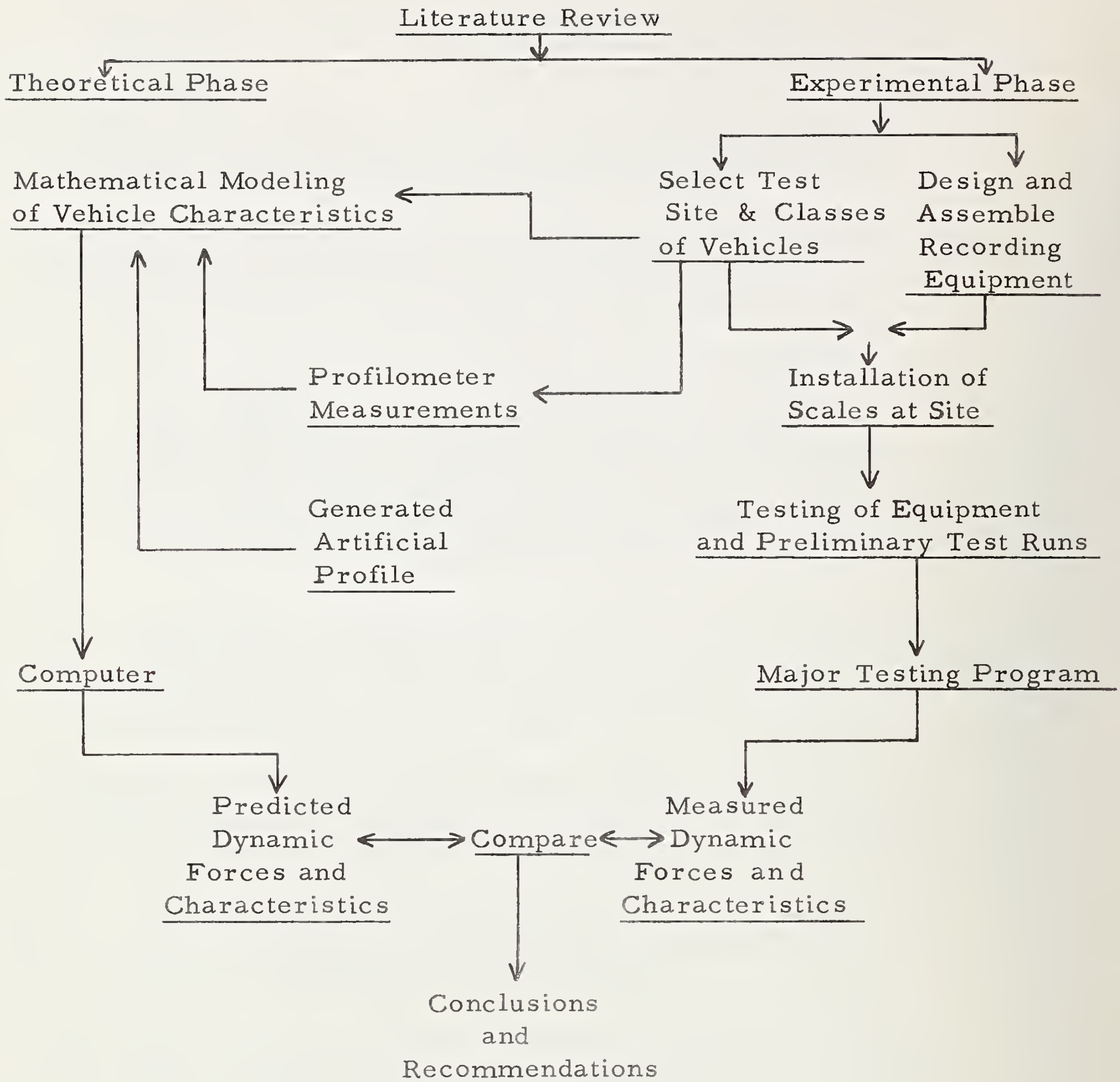


Figure 2. Scope of University of Texas Study (5).

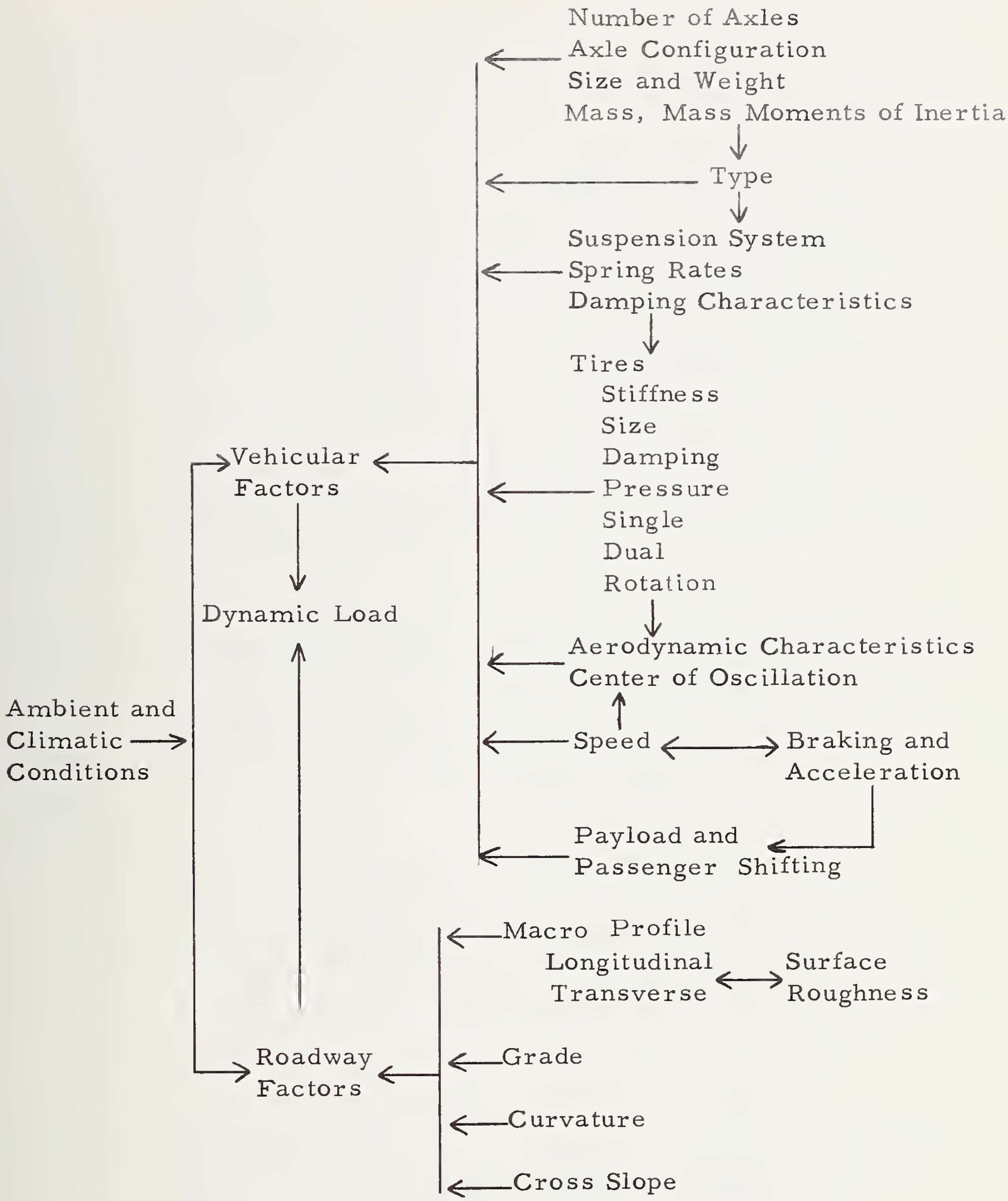


Figure 3. Vehicle - road interaction.

1. Single factors

    a. Axle

    b. Sample location

    c. Speed

    d. Roughness

2. Two-factor interactions

    a. Speed sample location

    b. Roughness sample location

    c. Axle speed

    d. Axle sample location

    e. Axle roughness

    f. Speed roughness

3. Three-factor interactions

    a. Speed roughness sample location

    b. Speed sample location axle

    c. Axle sample location roughness

    d. Speed roughness axle.

Although this work was excellent, the technique used to estimate the static weight from the dynamic load data was not of the same quality. It was based on an average of the values measured while a wheel was on a scale. Considering the success of their prediction model, the availability of multiple samples per scale and multiple scales, it would have been more meaningful to fit the experimentally acquired data and predict intermediate values using an interpolative method, i.e., between experimental sample points, and estimate the static weight from the RMS formula or determine it from an intergral moment expression. An interpolative prediction technique was used with good results in a study performed at Franklin Institute (6).

In many in-motion weighing systems, the investigators also failed to realize the significance of the inertial contributions of the sensor platforms to their recorded data. In the work performed by D. Blythe, et al. (7), it was acknowledged that:

1. Deviations of the dynamic axle weight over a range of crossing speeds follow a pattern for a given approach and site condition. (Essentially this same conclusion was reached by Philco (3) in the use of multiple Clyde-Lee-designed scales.)

2. Preloading of scales (which is always emphasized in literally all of the in-motion weighing studies) does not reduce the differences between the observed dynamic loads and the static loads (nor does it improve the response dynamics which frequently mask

the vehicle's dynamic signal). It does stabilize the weighing system and increase the consistency of the observed relationship between the dynamic and static loads.

In a summation of the overall results of the work performed on the Kentucky System (8), J.H. Havens reported, in June of 1971: "Despite overwhelming hardware failures which beset us in the development of an automatic in-stream vehicle weighing system - which we are now convinced we must abandon - significant measures of success were achieved. In other words, we have created an automation which almost works. The decision to abandon the prototype installation arose from pilot operations and proof testing. The basic defect is in the weighing platform in the pavement. Unfortunately, it is a design defect.

"Tie rods anchoring the platform in the pit induce a purposeful preload on the load-sensing elements. These tie rods change the preload as the temperature fluctuates. Thus, the balance or null point drifts. The noticeable effect was a triggering of the counting and weighing circuits when there was no live load on the platform. Since this load was not transient - but sustained - the circuitry "locked in" on the excess preload.

"The preload and tie rods were intended to keep the platform in firm bearing on the load-sensing units and to eliminate resonances and friction. Conceivably, it would be possible to control the temperature in the pit, but other factors were equally dissuasive.

"The pit structure extends almost four feet below pavement elevation. Access is made by removing the top plates. Whereas walk-in pits were constructed in the entrance ramp to weighing station on I 64, near Shelbyville (Westward side) and on a farm road at the University of Kentucky, it seemed unnecessary to require this feature in roadway installations. In fact, we visualized a "lift-out" platform which could be replaced by a "dummy" if or when repairs were needed. We did not achieve the "lift-out" simplicity.

"In the recent past, opportunities to build automatic weighing systems into an Ohio River bridge were forsaken because there was no practical way to fit the platform into the deck system. Consideration was given to incorporating the device into a pit or cavity in the abutment. A later alternative considered was to build the pit and platform completely remote from the bridge - in a ramp section on an earth embankment. Fortunately, our suspicions regarding the reliability of the pilot installation prevented us from advancing any of the afore-said plans to the final design state.

"The development research on this project began in 1960 and was originally programmed by the Division of Planning [HPS -1 (22)]. Responsibility transferred to the Division of Research with HPS - HPR - 1 (25), FY 1963-1964. The project was contracted to the University of Kentucky Research Foundation until June 30, 1969. In December 1969, the Research Division was authorized to begin a pilot period of operation. Approximately $198,000 will have been expended in sustaining the project.

"Whereas an early decision was made to adopt the so-called "broken-back bridge" platform in order to achieve a triangular form of output wave as a wheel passed over the platform, others have developed a weighing platform which can be recessed into a pavement [requires only a 3 inch (7.62-cm) inset]. The wave form is trapezoidal and would not directly couple with the digitizing system we have. We understand that matching instrument packages will be available soon. This was a persuasive factor in our decision to discontinue this project."

This project illustrates the need to consider the dynamic characteristics of the loading generated by the interaction of the vehicle, the road (or deck), and the weighing sensor. The system described above was not sufficiently responsive to the dynamic loading function of vehicles and did not adequately account for its own influence in the measurement process.

Passage Time

Assuming the data on the International tractor and Fruehauf trailer, shown in Figure 4, is still correct (1955 data), the time between events (TBE) shown in Table 1 will be used as the standard operating time-frame.

Table 1. Standard 3S2 truck TBE (9).

Velocity mph (1.609 km/hr)	Time (sec)			
	Tractor		Trailer	
	Front 1st Dual 11' 2" (3.404 m)	1st Dual 2nd Dual 4' 0" (1.219 m)	2nd Tract. Dual 1st Trail. Dual 16' 9" (5.105 m)	1st Trail. Dual 2nd Trail. Dual 3' 10" (1.168 m)
10	.75	.273	1.14	.262
20	.375	.136	.57	.131
30	.25	.091	.35	.087
40	.126	.088	.29	.065
50	.15	.055	.23	.052
60	.125	.045	.175	.043
70	.107	.039	.16	.037
80	.093	.034	.145	.032
90	.083	.030	.12	.029
100	.075	.027	.115	.026

From Table 1, it can be shown that the shortest TBE to be dealt with is the time between the sets of dual wheels on the tractor or on the trailer, about .026 - .027 sec (26 - 27 msec). This will be the worse-case operating time for the transducer and the logic contained in the system. Although fast in terms of mechanical response, 26 msec is fairly slow in electronic terms. Most of the modern strain guages operate at least a magnitude faster and some operate two magnitudes faster. The analog and digital circuits operate with no problem up to 1 msec.

Array Design

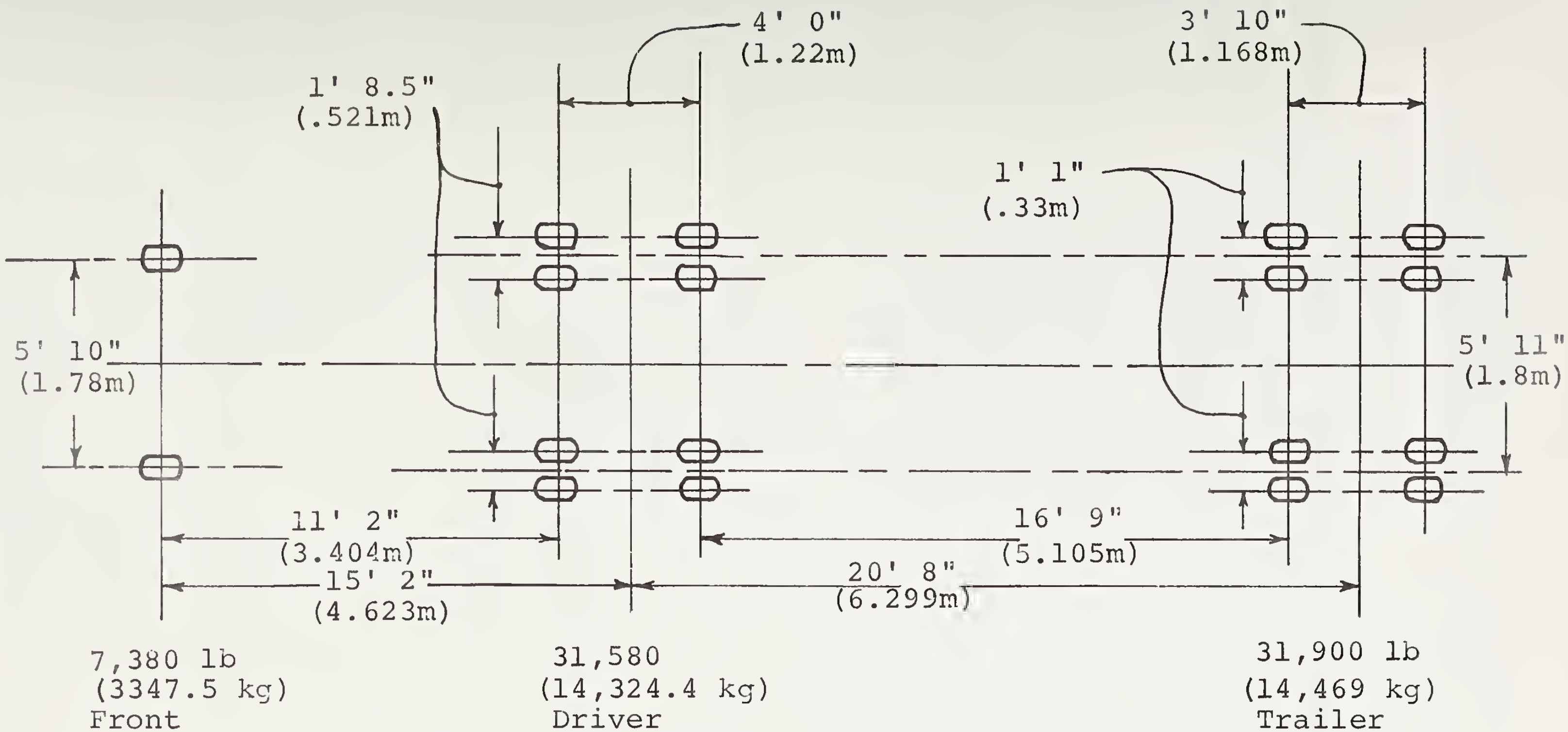
Designing an array for determination of the "dynamic weight," "static weight," and "dynamic factor," one must consider the spacing between the array element, the number of elements, and the time the single element has to operate during the event, as well as the time the truck is active in the array.

Since we are looking for axle weight and count, we will be processing two or more axles in the array. This is especially true in the case of the driving duals or tractor duals on a 3S2 truck, as shown in Figure 4, where the axles are spaced at 4 ft - 0 inch (1.219-m) and 3 ft - 10 inches (1.168-m), respectively.

The number of elements in the array can vary from a single detector to any number that one can place on the bridge. The number of elements will determine the accuracy of the data.

The problem with one sensor at a fixed place on the bridge, when dealing with dynamic weight, is predicting or knowing the precise action of the bridge dynamic (compression or expansion) and the position (as well as phase) of the truck suspension.

From the massive studies and documents available showing great variations in the dynamic weights of similar vehicles, it can be shown in the literature (5) that measured factors show ranges from 1.8 to 2.5. Appendix C of this report illustrates that, when all of the trucks and bridge components are in phase, the factor may exceed 2.5.



Tire Size = 10 x 20

Air Pressure = 70 psi (70.307 gm/cm^2)

= Approximate tire surface in contact with the slab.

Figure 4. International tractor and Fruehauf trailer (9).

If one sensor will give an error of 2.5x (250 percent), it must be determined what number of sensors will give an accurate dynamic weight.

If a frequency is assumed for the sine waves of a compressive frequency between the truck suspension (2-4 cps) and the bridge (x3.0 cps) of three cps (Figures 5 and 6), some idea of the overall spacing required can be determined.

On interstate highways, normal speed limits are currently 55 mph (88.5 km/hr) (max) and 45 mph (72.41 km/hr) (min). If limits are set on the velocity that occurs on the bridge, a reasonable level (for design only) would be 20 mph (32.18 km/hr) (min) and 80 mph (128.72 km/hr) (max), with a design center near the legal speed limit.

Period spacing for these velocities are shown in Table 2.

Table 2. Period spacing (fast).

Frequency (cps)	Velocity (ft/c)		
	29.4 fps (8.96 m/sec) 20 mph (32.18 km/hr)	75.5 fps (23.01 m/sec) 50 mph (80.45 km/hr)	117.6 fps (35.84 m/sec) 80 mph (128.72 km/hr)
	Linear Frequency (ft/c) (.3048 m/c)		
2	14.7	37.5	58.8
3	10.0	25.0	40.0
4	7.3	18.7	29.9

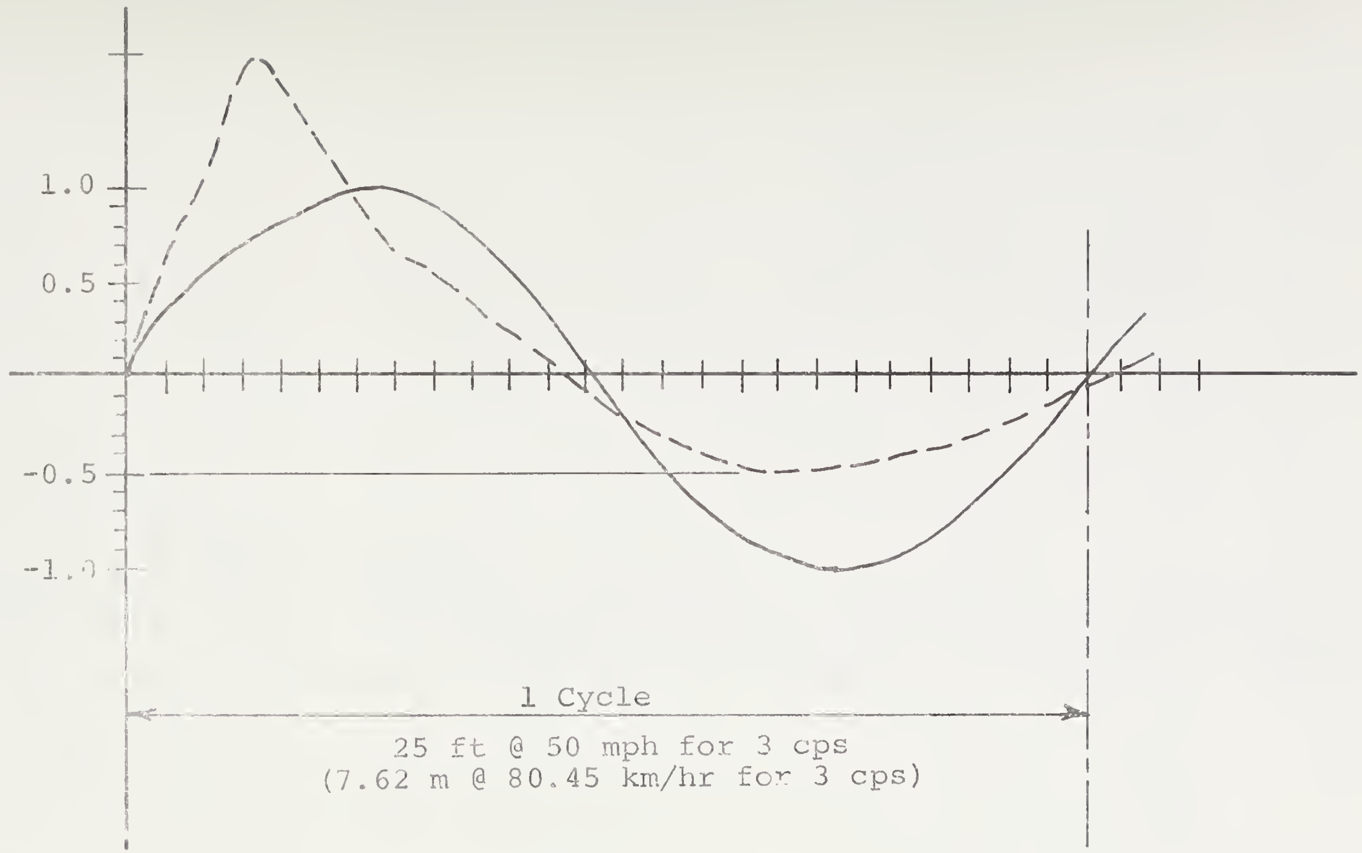
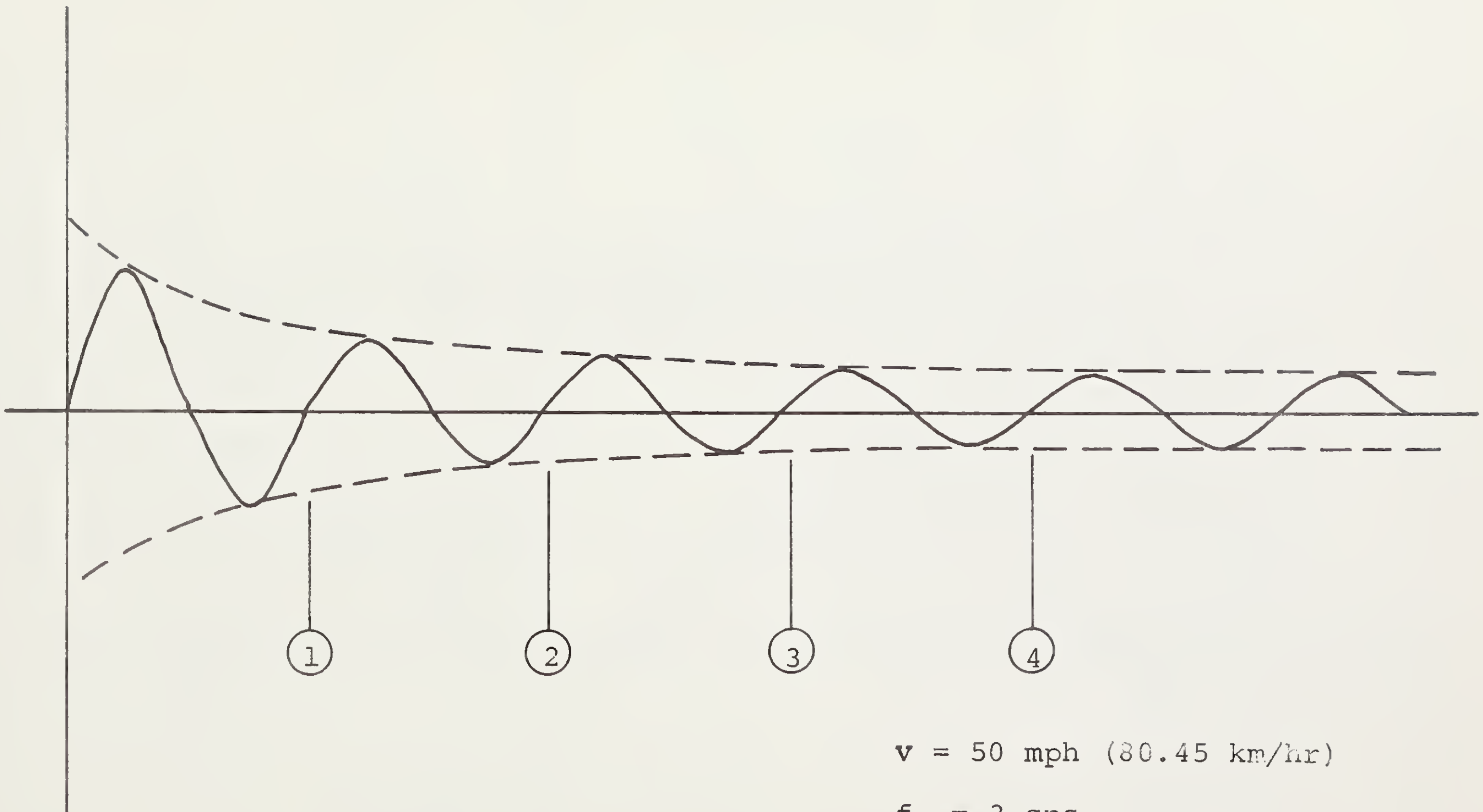


Figure 5. Typical cyclic period for 50 mph (80.45 km/hr) @ 3 cps.



v = 50 mph (80.45 km/hr)

f_N = 3 cps

Cycle = 25 ft (7.62 m)

Figure 6. Theoretical damping.

At a frequency of 3 cps and a velocity of 50 mph (80.45 km/hr) there is period or cyclic spacing of 25 ft (7.62-m).

Some problem areas result from this that are of concern in the array design and the computing logic:

1. Axle spacing - More than one set of axles will be into the array at one time (assuming the array will cover the full period).

2. Following Distance - With known following distances to be down to 15 ft (4.57 m) between trucks (nose to tail), the front axle of the rear truck may be into the array before the rear axle of the front truck clears the array.

The axle travels a distance of 25 ft (7.62 m) while transversing a full suspension/bridge cycle (Figure 5). It should be pointed out that the longest dynamic load expected on the bridge may not be detected in any given cycle for a given vehicle at any given speed. This point or points will be distributed over the bridge, but within 35 ft (10.688 m) (damping area) of major surface variation [above 3/8inch (.0525 cm)] (5).

If the array is maintained at least 35 ft (10.688 m) from the entrance to the bridge and that far away from the expansion joints or span junctions, it should be on a relatively smooth surface where the cyclic variations caused by the suspension can be observed. On the smooth bridge deck surface, the variations should be fairly fine grain and low profile. The time contrast area should cancel out most of the variations. It can be concluded, then, that if the load of one full

cycle can be determined, a good sample of the actual dynamic weight can be derived.

The proposed arrangement for the sensor is shown in Figure 7. Six sensors will be placed in the pattern of the wheels on one side of the truck. Results of the literature search have shown that the sampling of only one side is accurate when operating on a smooth, flat, and level surface, such as a bridge deck. The shaded areas in Figure 7 indicate the coverage of the radar antenna used for the passage and velocity detector.

The insertion of several transducers in sequential slots in the deck, 4-ft (1.22-m) apart, will weaken the deck to some extent, depending upon the dimensions of the slots. A minimum width and depth is essential to maintain maximum structural integrity of the deck for the array shown in Figure 7. This array will provide the best approach for characterizing an arbitrary truck's dynamic function with a minimum number of transducer installations.

Two other basic array designs were considered in order to reduce the deck-weakening effect:

1. An angular array of three full-length transducer installations extending across an entire lane

2. An alternating array of the one-half lane width transducers such that three of the transducers are in the right half of the lane and three are in the left half of the lane normal to the direction of flow.

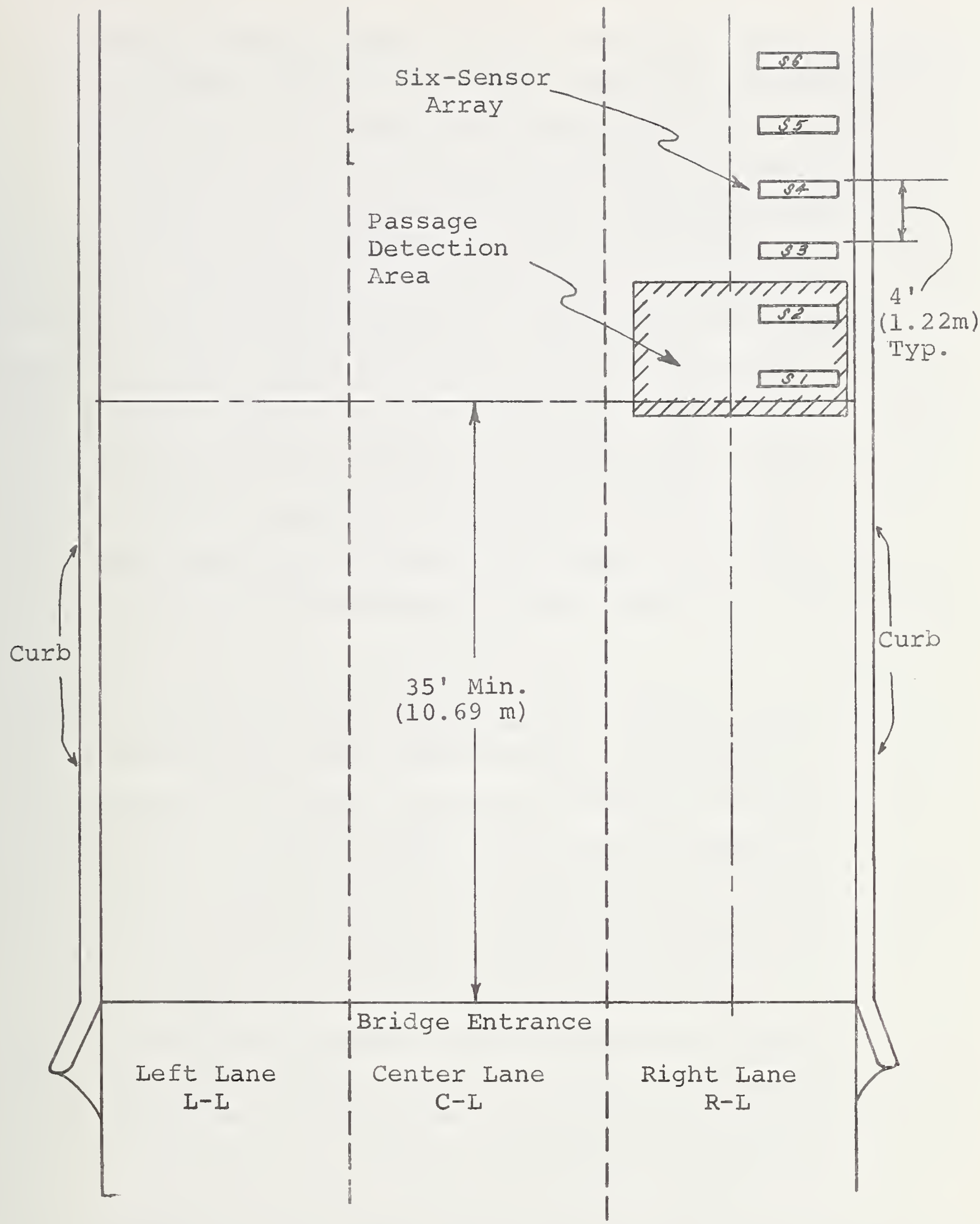


Figure 7. Position of sensors on bridge.

An analysis of the angular form of array, using a single long transducer, indicates that real difficulties will be encountered in trying to separate individual axle signals for trucks with dual wheels and tandem axles. If an angle is chosen that allows a continuous signal for one set of duals at one end of an axle and an adequate lag time between the left and right duals of an axle to allow signal separation, and the axle is one of a tandem axle set, signal separation of the opposing duals on the two axles cannot be accomplished. Conversely, if an angle is chosen that will eliminate the tandem signal separation problem, signal separation of the duals on each end of the axle cannot be accomplished. If such an approach were attempted, an immense increase in the cost of both the acquisition hardware and the reduction process would be encountered in trying to separate axle signals.

An alternative angular array approach using two short transducers in the same long angular slot eliminates the axle signal separation problem. However, it is of the same form as the alternating normal array mentioned in 2 above. This form of angular installation does not provide any benefits beyond reduction of the number of slots in the longitudinal direction. In fact, it provides a poorer signal than the alternating normal array because of the longer stay time of the tire on the transducer and the initial and final partial loading of the transducer due to the angular approach. This creates added complications in processing the axle signals to measure the dynamic wheels(s) load.

The alternating normal array mentioned in 2 above appears to be the second best form of installation. As a minimum, approximately three half-lane slots would need to be cut in

each of the left and right halves of a lane. This approach, like any other which measures the loads of the wheels at opposing ends of the same axle, requires a flat smooth deck. Any slope in the deck will tend to induce load shifting due to roll of the vehicle. Given no other complications, it is possible to average out the load shifting effect if both ends of an axle were measured simultaneously. However, to do this and still obtain the total number of samples necessary would require six slots completely across a lane and twelve transducers, which is not desirable. This implies that the roll effect remains as a problem in the alternating array approach. To further complicate the problem, it must be pointed out that the dynamic behavior of the two ends of an axle will, in most cases, be significantly different. It is possible that the basic behavior, due to the main suspension system, will be similar, but the higher frequency components cannot be assumed to be anything but dissimilar because of variances in tire wear, road roughness, etc. Any attempt to combine three samples from the right end of an axle and three samples from the left end of the axle to characterize a single wheel or dual wheel dynamic load function for a given truck is fraught with difficulties that will immensely complicate the reduction process and significantly increase its development and operational costs.

The use of the single-side array (Figure 7) provides the most effective, reliable, and economical array approach. Rather than wasting resources in trying to use two-sided arrays, as discussed above, to minimize the weakening effect of slots cut into the deck, such resources should be used to minimize the size of the transducers requiring such slots or in developing the thin-pad-type transducers.

FUNCTIONAL REQUIREMENTS

As was indicated earlier, the most pragmatic approach to the acquisition and recording requirements was to reduce the desired set of acquired variables to a minimum essential set. This approach also directly affects the hardware requirements of the acquisition and recording portion of the system. It minimizes the sensor, transmission, processing, and recording hardware by eliminating redundancy of acquired information. It does place a larger burden on the reduction portion of the system. However, the reduction process can be performed completely on a general-purpose digital computer, if the output from the recording hardware is digital and readable. This further minimizes the special hardware necessary to the system.

In order to properly acquire the minimum set of variables, both categories, i.e., direct and indirect, of dynamic load sensors must perform the following functions:

1. Detect the arrival of a vehicle

2. Determine, via a synchronized clock, the time of arrival, t

3. Determine the lane of occupancy of the detected vehicle

4. Determine the dynamic load imparted to the deck by each wheel of each axle as the axle passes through the dynamic load sensor's field, and the time of the axle sensing

5. Determine the velocity of the vehicle as it passed through the load sensor's field

6. Determine when the vehicle had completely passed through the sensing field, i.e., distinguishing between vehicles

7. Retain the above-acquired data in a temporary data storage buffer.

In the case of the direct sensor measurement category, two additional functions should be performed:

1. Calculate the axle dynamic loads for all sensed axles of each vehicle from the sampled wheel load

2. Test the calculated dynamic axle load versus the dynamic load equivalent of 2,000-lb (907.18-kg) axle weight static load for each axle. An alternative approach which was identified was to convert each dynamic axle load to a static load equivalent and test against the 2,000-lb (907.18-kg) axle threshold. This requires more operations than the use of a threshold set at an equivalent dynamic load value, assuming that the dynamic load was the variable acquired. If no axle load for the detected vehicle exceeded the established threshold, the acquired data would be discarded. If any axle exceeded this threshold, the data acquired would be saved on a computer-readable storage media; i.e., the data buffer would be dumped to the storage media. In either case, the

temporary storage media would be reinitialized and made available for a subsequently detected vehicle.

The indirect-category type of system can also perform a function that is analogous to the above-defined axle threshold elimination. However, separate wheel loads will probably not be discernable, although a lumped axle measurement will be available. This measurement will not be dynamic axle load, but will be a resultant factor. Consequently, an equivalent 2,000-lb (907.18-kg) axle threshold for this factor must be calibrated for each bridge in order to accomplish such a function with the indirect acquisition and recording on-site hardware. Since some increase in dynamic load occurs with vehicle speed (3), (4), (5), it may be necessary to perform this function for the indirect category using a variable threshold as a function of speed.

The temporary data block storage capability of the acquisition system would be sufficient to handle all lanes, in a parallel manner, and within each lane, sufficient to allow dumping and reinitializing of a data block memory to keep a ready data block for each newly detected vehicle.

The structure of the data block and the accumulated data blocks on the computer-readable storage media must be designed for efficient data reduction.

Acquisition System Design Characteristics

The acquisition system desirable should be designed with the following characteristics:

1. The system should be easily installable on an arbitrary bridge, requiring minor and minimal operations to the bridge structure.

2. It should be easily removable from an arbitrary bridge.

3. It should be weatherproof, although it would not be essential that it be capable of operating under all weather conditions, e.g., snow or ice-covered decks, etc. However, all components of the system should be adequately protected for all weather conditions.

4. It should be easily transportable, although not necessarily mobile.

5. It should be capable of sustained operation in an unmanned manner, i.e., automatic, with an independent power source and adequate means of storing the acquired data. The length of such sustained operation should have a design objective of 7 days and a minimum capability of 24 hr.

6. It should be easy to maintain.

7. The data storage media should be minimally of a modular form allowing easy removal of the recorded units and replacement with unrecorded units. On-line transmissions to a central facility should be investigated. However, it should not be considered essential to the system for the dumping of acquired data.

8. The system's appearance, especially the recording instrumentation and the sensors, should be inconspicuous to the occupants of the passing vehicles, when in an installed state.

9. The system should be designed to maintain its physical integrity; i.e., it sould be designed to inhibit vandalism, theft, etc., because of its unmanned operating capability.

10. The system should be fully digital and designed for maximum compatibility to the data-reduction computer program system, which would be digital. This would increase the reliability of the data reduced by the data-reduction process.

11. The sensors selected to sense the dynamic truck axle loads would need to be capable of responding to rapid variations in loads.

12. The dynamic load sensors should not introduce any inertial effects into the resultant measurements.

13. The dynamic load sensors should have no natural frequencies in the low range, i.e., 0 to 50 cps.

14. The dynamic load sensors should not perturb vehicle dynamics.

15. Any roadside recording and processing equipment should be inconspicuous.

16. Supporting speed, passage, etc., sensors should be:

    a. Lane-dependent

    b. Easily integratable with the load sensors

    c. Installable in an inconspicuous manner

    d. Desirably packaged with the load sensors as a "sensing package."

Acquisition System Design Constraints

The following constraints are imposed upon the acquisition system:

1. The data block, as defined in the portion of this section which describes the reduction requirements, would be required to have an end-of-record indicator following the set of data on the last axle of each vehicle measured and recorded.

2. The last data block recorded would be followed by an end-of-record mark.

3. The system would have a field of view adequate to account for lateral variation in the position of any given vehicle within any given lane.

4. Because of the need to simultaneously acquire data in more than one lane, it is necessary to dedicate one sensor "package" to each lane. An alternative,

if possible, would be to sense in all lanes with a single sensor system in a sequential fashion and to route the data for a specific lane to a buffer dedicated to that lane or to use a random buffer access method.

5. Additionally, the data acquisition and transmission rates could necessitate a multiple buffering system for each lane where the next data buffer is being filled while previous ones are being dumped.

6. The installation of the direct form of sensor system must consider the vehicle-road dynamic interaction for each type of truck and their geometric axle configurations. An arbitrary installation could provide little, if any, informative load data; e.g., deck roughness could induce wheel-hopping which could cause the vehicles' wheels to partially or totally miss the sensor.

7. The installation should be made in a flat portion of the deck to prevent load shifting due to vehicle roll. This will allow single wheel sampling and greatly reduce hardware requirements.

8. The installation should be made on the smoothest possible portion of the deck and should be approximately 35 ft (10.668 m) from the nearest deck surface perturbation to allow damping of the perturbational effect.

The constraints identified in 4 and 5 above are sensor- and acquisition-hardware-dependent and can only be established

after the specific hardware is identified.

In considering the geometry of various truck types, primary consideration should be given to the 3S2 type. The 3S2 type makes up a large percentage of the heavy highway vehicle population. This was evidenced in the survey made by Graves (10) and in other truck surveys. However, the installation design should not be oriented to this type to the exclusion of any other truck type.

A statistic that could prove of significant value in further reducing the sensor system is illustrated in the survey performed by Alexander and Graves (11). In rural areas, 90-96 percent of the truck traffic occupied single lanes -- the right lanes, in most instances -- of four-lane highways. In urban areas, this percentage decreases, but it would appear that a similarly large segment of the truck population would consistently occupy two or three particular lanes of a multi-lane highway, as opposed to random occupation of all available lanes. This implies that serious consideration should be given to only instrumenting the truck-used lane(s) of bridges, rather than all of the lanes on a bridge. Significant savings could be achieved on the on-site hardware. Also, this would act as an automatic filter for a large portion of light vehicle traffic, particularly automobiles; i.e., most automobile traffic would not enter the system at all.

LISTING AND DESCRIPTION OF SENSORS

It was indicated earlier that this study was primarily concerned with the identification of sensors which were exotic or unexploited in the field of auto-truck transportation. However, to preclude the possibility of overlooking a candidate sensor, a thorough investigation of sensors used in various highway, traffic, and bridge applications was performed. A thorough investigation of unclassified work by the Department of Defense (DOD) in related areas and in the area of intrusion and security detection sensors was made. Other areas were also investigated for the existence of a potentially usable sensor, such as intruder detection devices used in civilian security and law enforcement. A comprehensive, but not totally exhaustive, list of sensors is presented in Table 3. A large number of the sensors identified in Table 3 were previously identified in a survey made by Texas Instruments (1). This list does not attempt to identify all of the transducers available. Certain areas have been defined only by a generic title. Comprehensive lists and descriptions are readily available from other sources (12). The primary concern in this study has been to identify specific transducers capable of acquiring a direct or indirect indication of the dynamic wheel or axle load of a highway vehicle and to identify supporting sensor requirements, if they exist, for each of the dynamic load sensors.

Load Sensors

The list of candidate sensors which could provide the variables necessary for the "in-motion" bridge weighing system are shown in Table 4. The dynamic load sensors are specified

Table 3. Basic sensor list.

Type	Transducer	Single Sensor Sensed Data								
		Presence	Mass	Speed	Axle (Shape)	Engine	Size	Fuel	Type Data	Aspect Angle
Compressive	Piezoelectric Magnetostrictive (triboelectric) Strain gage Elastomers Conductance (capacitance) Hydraulic Pheumatic Electronic scale	X	X		X		X		X	
Acoustic	Microphone	X				X				X
Seismic	Geophone Seismometer	X	Indirectly X		X	X Qualified	X		X	
Electro-magnetic radiation sensors (vehicle source)		X				X	X			X

Table 3. Basic sensor list (Continued).

Type	Transducer	Single Sensor Sensed Data								
		Presence	Mass	Speed	Axle (Shape)	Engine	Size	Fuel	Type Data	Aspect Angle
Magnetic	Flux-gate magnetometer Thin-film magnetometer Induction coil magnetometer Optical pumping magnetometer Loop detector Magnetic gradient detector Field asymmetry sensing Hall effect devices	X		X Qualified	X	X	X		X	
Gravitational	Gravimeter		X							
Aerodynamic	Schlieren detector Interferometer Microbarograph	X					X		X	

Table 3. Basic sensor list (Continued).

Type	Transducer	Single Sensor Sensed Data								
		Presence	Mass	Speed	Axle (Shape)	Engine	Size	Fuel	Type Data	Aspect Angle
Chemical	Condensation nuclei Honeywell Ionization Surface adsorption Chemiluminescence Flame ionization Flame photometric Intrared adsorption Electron capture Thermal conductivity Kryptonate UV-derivative IV-correlation Mass spectrometer Plasma chromatograph	X				X			X	
Electromagnetic (EMI)	Induction coil	X					X			X

Table 3. Basic sensor list (Continued).

Type	Transducer	Single Sensor Sensed Data								
		Presence	Mass	Speed	Axle (Shape)	Engine	Size	Fuel	Type Data	Aspect Angle
Scattering (artificial or natural energy sources)	Radar Pulsed CW Doppler Interrupted beam RF Laser IR Photocell Laser radar Active IR Passive IR Video scanner Television Photograph Radiation Proximity fuze Sonic Pulsed CW-Doppler	X		X Doppler or Range Rate	X Qualified by Specific Sensor		X		X	X
Electric or natural electromagnetic field	Electrometer High Z vacuum tube Gold leaf Capacitive detector									

Table 4. Candidate sensors.

Sensor	Measured Variable								
	Dynamic Wheel Axle Load	Static Wheel Axle Load	Pas-sage	Speed	Axle Pas-sage	Lanal Posi-tion	Axle Spacing	No. of Axles	Headway
Direct Form									
Pressure transducers									
Magnetostrictive (triboelectric)	X	X (a)	X	X (p)	X	X (c)	X (d)	X (e)	X (f)
Conductance pad (capacitance)	X	X (a)	X	X (p)	X	X (c)	X (d)	X (e)	X (f)
Piezoelectric	X	X (a)	X	X (p)	X	X (c)	X (d)	X (e)	X (f)
Strain gage	X	X (a)	X	X (p)	X	X (c)	X (d)	X (e)	X (f)
Elastomers	X	X (a)	X	X (p)	X	X (c)	X (d)	X (e)	X (f)
Electronic scale	X	X	X	X (p)	X	X (c)	X (d)	X (e)	X (f)
*Indirect Form									
Seismometer		X (a)	X		X (g)	X (h)	X (i)	X (j)	X (f)
Geophone		X (a)	X		X (g)	X (h)	X (i)	X (j)	X (f)

*This study contractually did not include the classic use of bridge strain gage measurements, i.e., beam bending moments, etc.

Table 4. Candidate sensors (Continued).

Sensor	Measured Variable								
	Dynamic Wheel Axle Load	Static Wheel Axle Load	Pas-sage	Speed	Axle Pas-sage	Lanel Posi-tion	Axle Spacing	No. of Axles	Headway
Support Sensors									
Radar									
CW			X	X (k)	X (l)	X (c)	X (d&l)	X (e&l)	X (f)
Pulse			X	X (k)	X (l)	X (c)	X (d&l)	X (e&l)	X (f)
Doppler			X	X	X (m)	X (c)	X (d&m)	X (e&m)	X (f)
Acoustic (directed microphone)			X		X (n)	X (c)	X (d&n)	X (e&n)	X (f)
Ultrasonic									
Pulse			X			X (c)			X (f)
Doppler-CW			X	X		X (c)			X (f)
IR									
Passive			X	X (k)	X (o)	X (c)	X (d&o)	X (e&o)	X (f)
Active			X	X (k)	X (o)	X (c)	X (d&o)	X (e&o)	X (f)
Photocell			X						X
Video									
Laser radar			X	X (k)		X (c)			X (p)
Magnetic transducers			X	X (k)	X	X (c)	X	X	X (p)
Induction loops			X		X	X (c)			

Table 4. Candidate sensors (Continued).

[a] The estimated static load determined during data-reduction process.

[b] Arrival time on passage sensing included by synchronous electronic clock in road-side processing equipment.

[c] Lane of occupancy determined from lane of sensor installation.

[d] Axle spacing determined during data reduction from axle arrival times and vehicle speed from supporting sensor.

[e] Number of axles determined during data reduction from axle arrival times and vehicle passage times per lane.

[f] Headway determined during data reduction from vehicle arrival times per lane.

[g] Axle passage determined during data reduction from seismic signatures.

[h] Lane of occupancy determined during data reduction by peak and time signature analysis.

[i] Axle spacing calculated from seismic signature data and speed from supporting sensor and/or recording speed (interval).

[j] Number of axles determined from seismic signature analysis.

[k] Derivable from range rate data or other available criteria.

[l] Signal/noise level may preclude this through the deck.

[m] Extraction via filtering of wheel rotation signal provides this variable.

[n] Wheel noise signal may be usable; no available evidence.

[o] Tire heat signal may be usable; no available evidence.

[p] The use of multiple installations of the direct form of dynamic load transducer will allow determination of vehicle speed, per lane, from the arrival times at each installation during the data-reduction process.

as forms of transducers. However, the support forms of sensors are only identified in a generic manner and are of much less importance. The direct forms of transducers shown in Table 4 are of the compression-sensing type.

All of the forms of the compressive-type transducers shown in Table 3 were considered. However, they all did not show sufficient merit to be included in Table 4.

As will be seen in the discussion of the various compressive-type transducers and in the discussion on the acquisition hardware, the candidate compressive-type transducers can be developed such as to allow geometrical and electronic interchangeability. This means that these transducers can occupy the same spatial geometry and, by providing a suitable electrical interface with each transducer, one of the other types of transducers can be replaced by unplugging one transducer and plugging in the other. Obvious benefits arise from this in a prototype development program.

Pneumatic-Hydraulic - Of the eight transducers shown in the compressive group in Table 3, the pneumatic and hydraulic forms were discarded early. Both were eliminated on the basis of response time and wear characteristics. The history of the pneumatic traffic sensor is as well known as its endurance capability. An application of a hydraulic form of pressure sensor in an English experiment (37) indicated a lack of sensitivity which further reinforces the decision to eliminate them from consideration.

Electronic Scales - In the case of electronic scales, the best available, in terms of size, appears to be of the type used by Al-Rashid, et al. (5), which was the Rainhart Company's Model 880. The standard Model 880 is 22 inches (55.88 cm) by 54 inches (137.16 cm) by 2-1/2 inches (6.35 cm). However, the version used in the study was 62 inches (157.48 cm) by 21 inches (53.34 cm) by 2-3/4 inches (6.985 cm). The use of this form of scale requires considerable excavation of a bridge deck, especially if used in a multiple installation configuration. Such an installation could be justified for a single experimental study, but it is not a practical approach for an easily installable system and it imposes the greatest structural changes to a bridge deck of all of the compressive-type sensors. On this basis, the electronic scale should only be considered if no other compressive type of transducer proves satisfactory. One distinct advantage of this particular electronic scale is that it has been used successfully.

Magnetostrictive (Triboelectric) Transducers - As a result of investigating military intrusion detectors and, to a much lesser extent, non-destructive materials testing techniques, it was determined that an excellent candidate for a compressive-type transducer is the magnetostrictive cable. In one study, the U.S. Army (13) experimented with the use of coaxial cable buried in the soil. If a load is induced in the vicinity of the cable, e.g., a man's weight, a current is generated due to excitation of one or more of the four modes, i.e., stretching, bending, tension, or uniform pressure. Axial stretching of the cable is the most efficient current generation mode. It generates a current three orders of magnitude larger than the other modes.

In the field tests made by the Army, all four modes were excited. The region of greatest current generation is that region which is closest to the load. Further, current maximizes when the load is directly over the cable. The sensor system tested by the Army could be set to trigger when a given load was within some small distance from the cable. The electronic logic was designed to respond to low-frequency signals of large amplitude. It was sufficiently sensitive to detect loads of over 100 lb (37.324 kg) and reject loads of under 20 lb (7.465 kg).

A similar device was developed by the U.S. Air Force (14). A nickel-rich plated wire was used in a coaxial configuration 164.04-ft (50-m) long. The sensitivity of the cable was sufficient to detect a man and still distinguish a heavy tank. Tests were run using different approach paths, i.e., perpendicular crossing, oblique crossing, and parallel. Test subjects included a man, a tank (tracked vehicle), a dog, a horse, and wheeled vehicles which gave satisfactory results. This cable could also be used as a magnetometer, if desired. The metallic design selected in this work did not have the best sensitivity of the designs investigated. However, it did attain nearly zero effect from magnetic influences, which had caused some difficulties in previous configurations.

The development of a truck axle load sensor using this phenomenon appears to be quite feasible. However, in order to practically utilize the magnetostrictive cable to weigh trucks in motion on a bridge deck, a suitable environment, i.e., supporting medium, must be established. In the case of the intrusion detection application, the cable was buried under several inches of soil. This allowed significant strain

to be imposed on the cable, i.e., due to the nature of the supporting medium. Since concrete is nearly an elastic material, the necessary excitation load cannot be transmitted to the cable if it is almost fully supported by the concrete deck. This implies the need to support the cable in a medium which will allow it to undergo adequate strain for current generation. A simple and readily available technique is to support the cable with an asphalt or elastomer material. A significant thickness of the supporting material is necessary to ensure adequate deflection of the cable. Since a 1/16-inch (.159-cm) bump on a road surface significantly perturbs a vehicle's dynamic response, a surface installation becomes impractical. This leads to the need to embed the cable in the bridge deck; i.e., a slot must be cut into the deck for each transducer to be installed.

The cable could be viewed as a transducer by itself. Considering it as such leads to an in-place embedding of the cable in some form of plastic or viscoelastic medium. Since the cable is strain-sensitive, extreme care would be required during installation to prevent inducement of an initial strain.

A low-penetration asphalt could be used as the supporting and transmitting medium. However, this approach is not recommended because of the non-standard installations which would occur and the need for significant recalibration and zeroing of the cable after installation. In all circumstances, calibration and zeroing will need to be at least verified after installation.

The most attractive approach is to prepackage the cable in a sufficiently responsive and durable elastomer. A rigid base

could be used to prevent distortion of the cable during installation and to assist in achieving a standardized installation, as shown in Figures 8, 9, and 10.

In order to achieve as nearly an instantaneous sample as possible, it is necessary that the transducer be as narrow as possible, i.e., length along the traffic flow direction. Further, to prevent inducement of significant torque about the longitudinal axis of the transducer, which could possibly lead to destruction of the transducer, and to prevent excitation of the torquing mode, which could create ambiguities in the general signal, the sides of the transducer require rigid support. This can be easily achieved by in-place pouring of concrete along the sides of the transducer, as illustrated in Figure 11. An example of a multiple installation is shown in Figure 12. Desirably, the cable to the on-site processing hardware would exit through a small hole through the deck from the bottom of the slot. Also, it would be extremely important that the plastic or viscoelastic supporting material was exactly level with the deck surface when cured. It should not evidence any creep or serious contraction as a function of temperature or applied load, but should effectively transmit an applied load to the cable, under all environmental conditions, in a consistent manner sufficient to excite the voltage-generating modes of the cable proportional to the excitation loading.

The installation of this transducer design would require a slot to be cut in the deck. Previous "in-motion" weighing systems were usually in the range of 56 inches (1.42 m) to 60 inches (1.52 m) in length. From a practical point of view, a length (L_L) of 42 inches (106.68 cm) appears to be

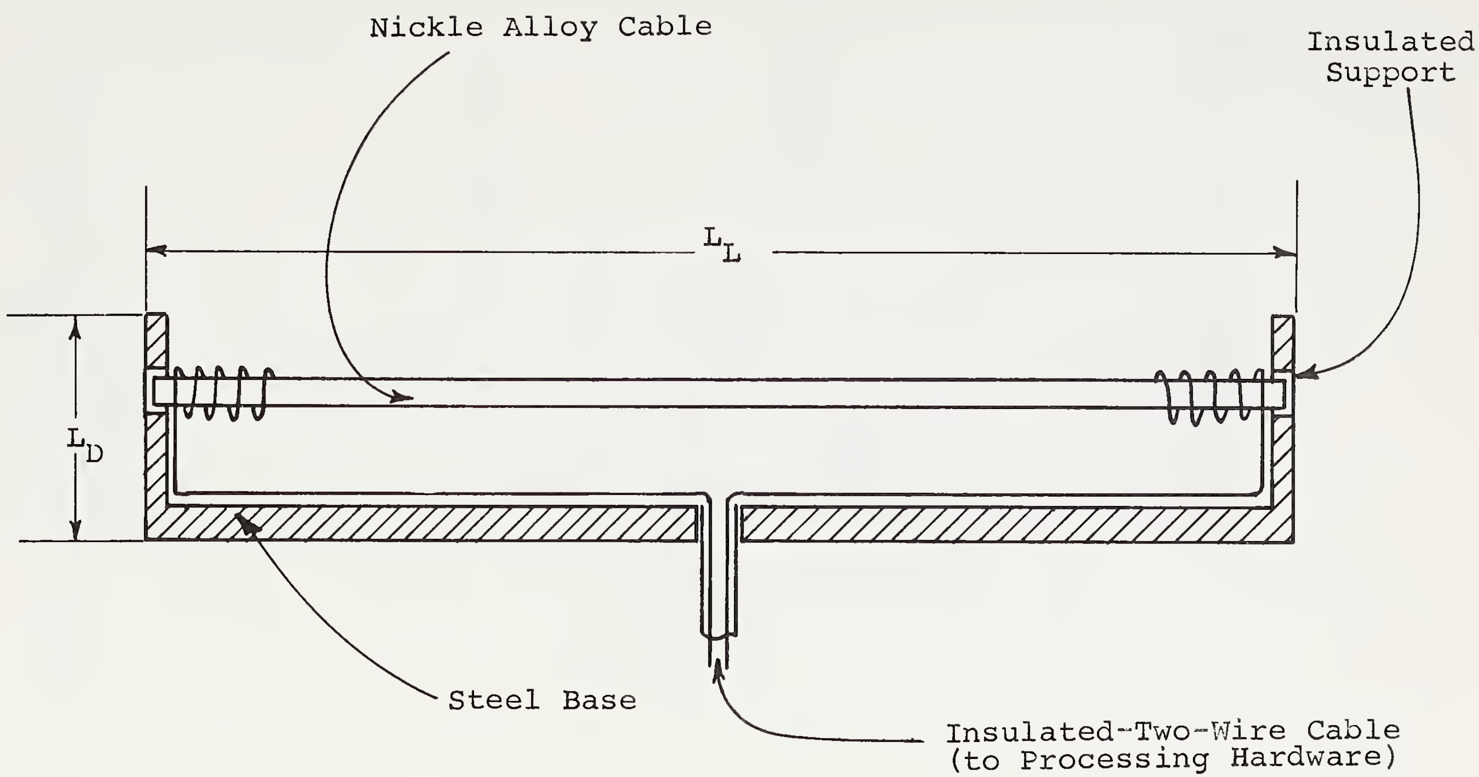


Figure 8. Basic magnetostrictive transducer.

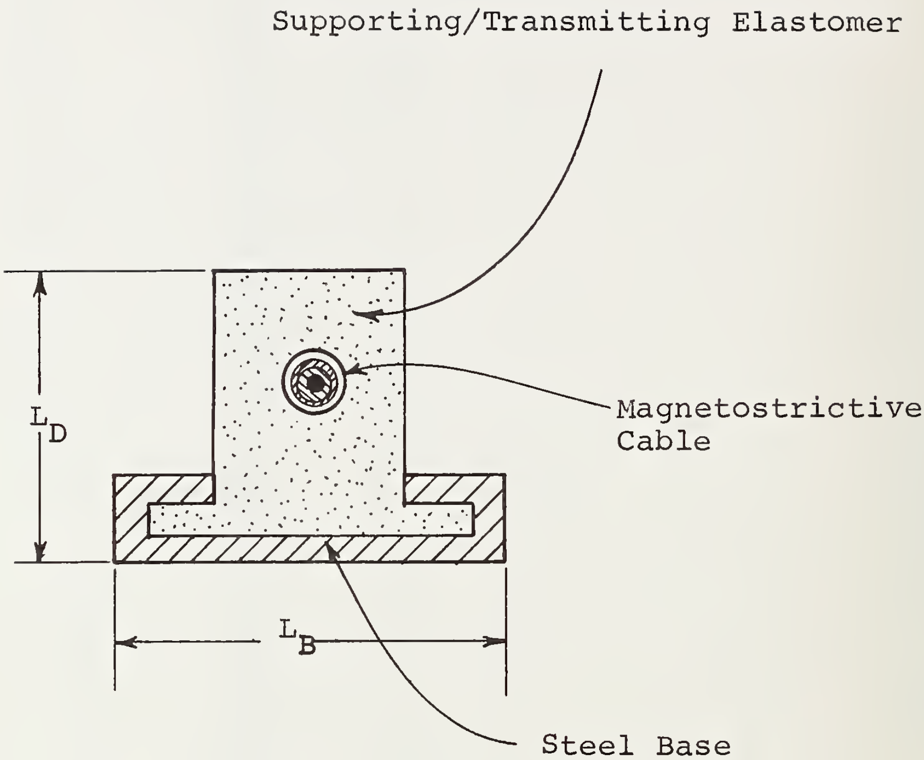


Figure 9. Cross-section of magnetostrictive transducer.

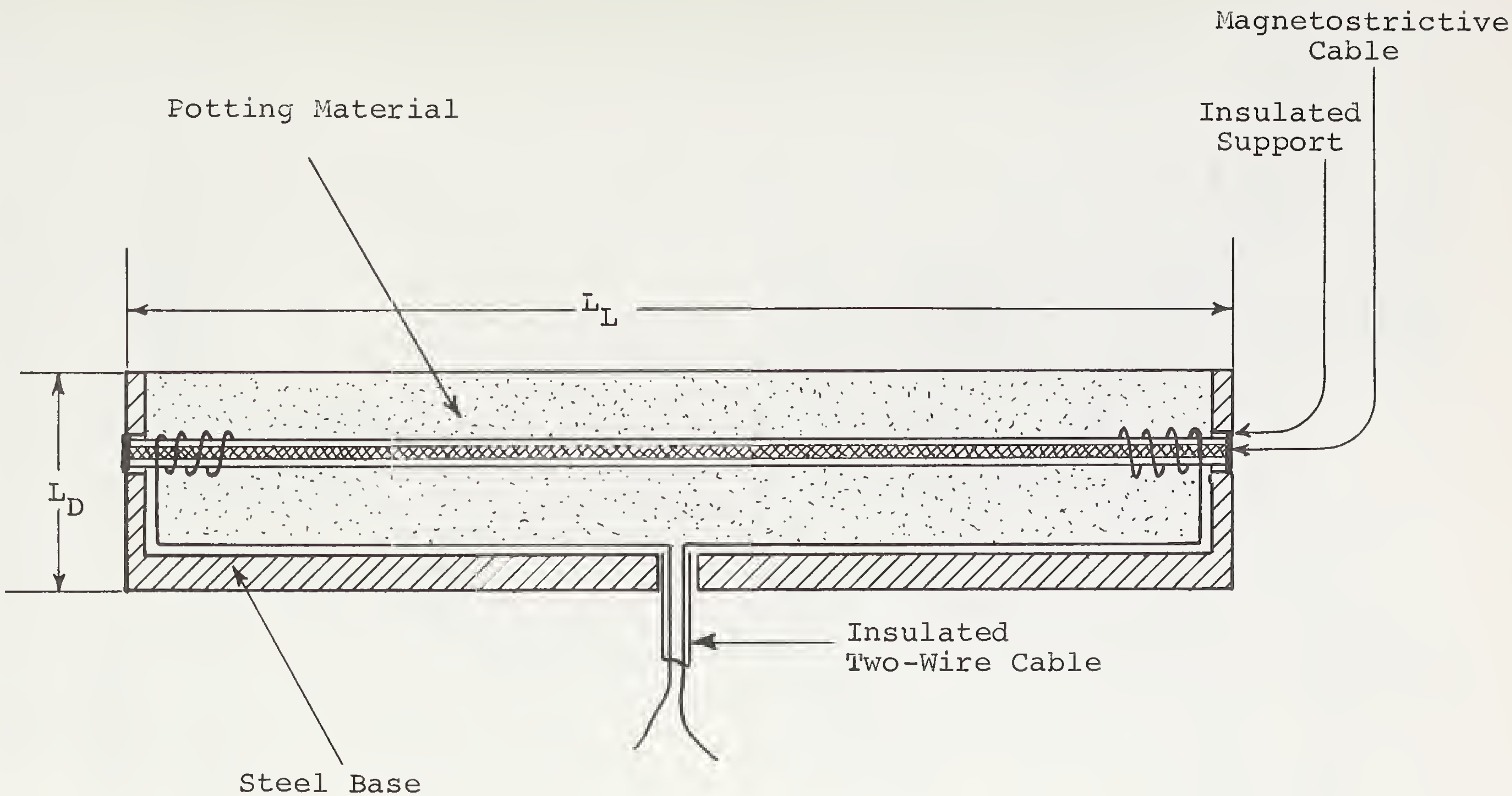


Figure 10. Longitudinal section of magnetostrictive transducer.

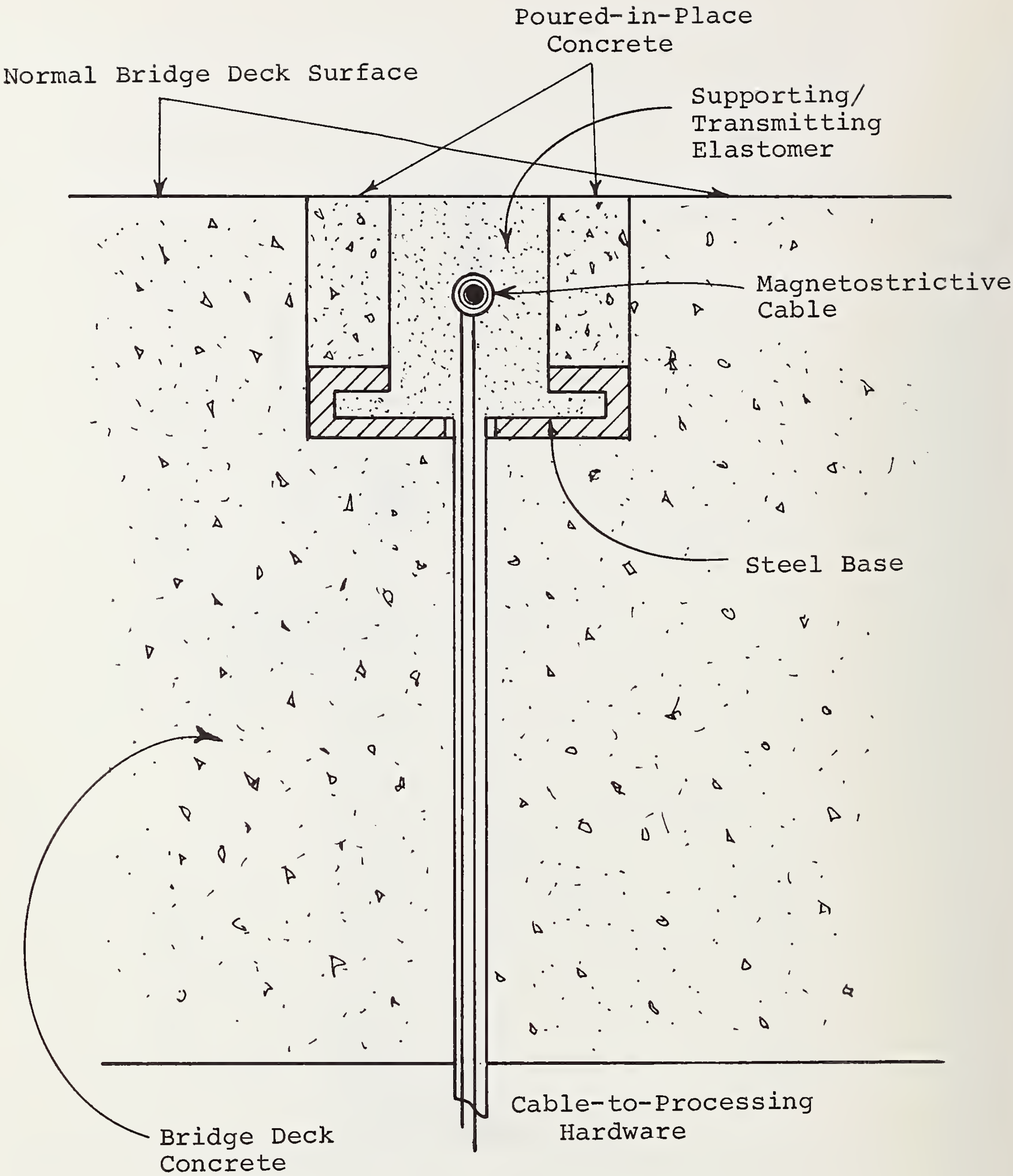


Figure 11. Installation of the magnetostrictive transducer.

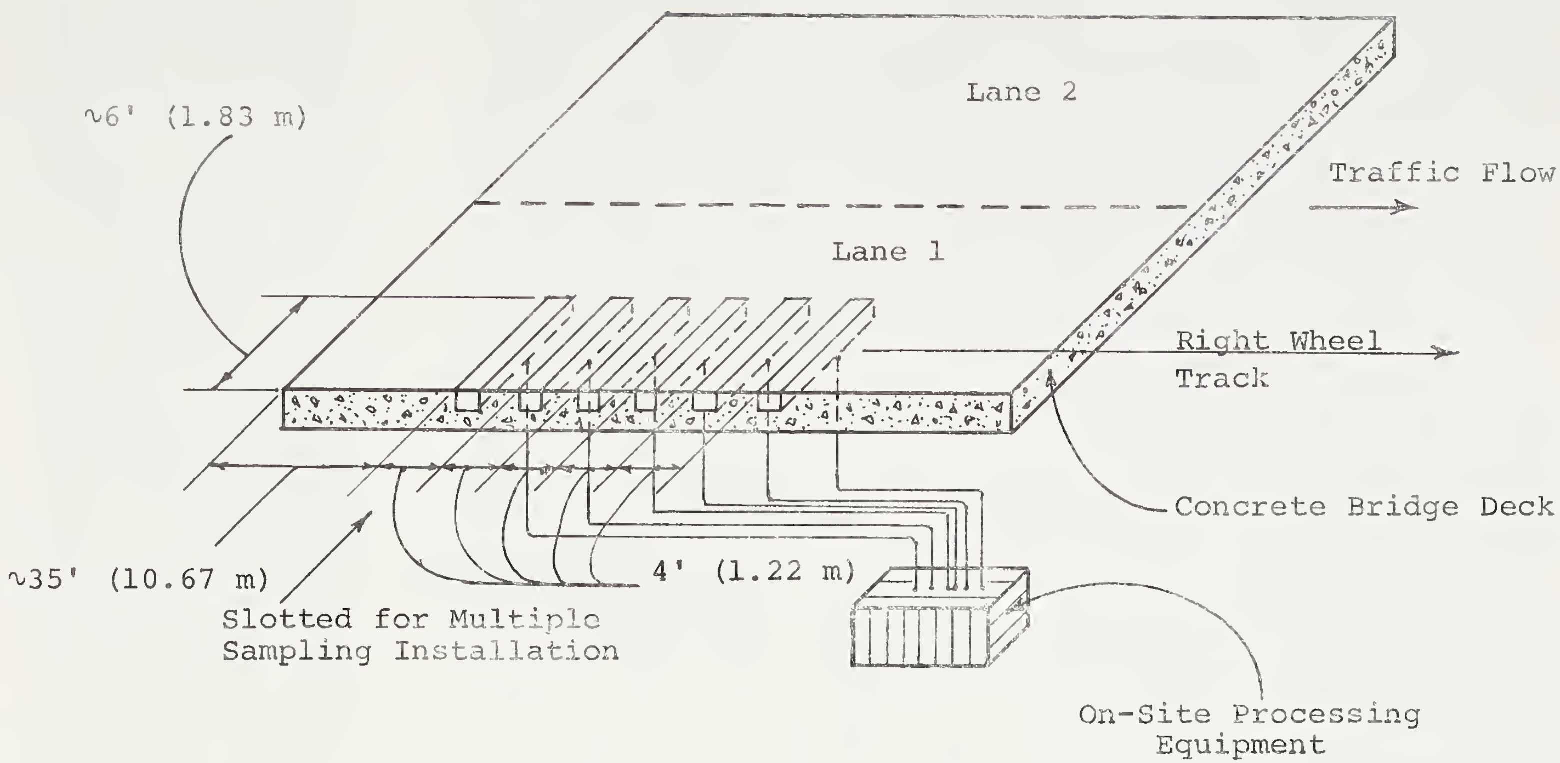


Figure 12. Example of multiple compressive sensor deck installation.

satisfactory. The depth of the slot (L_D) is largely a function of the diameter of the cable. A cable diameter of approximately 1/2 inch (1.27 cm) should be anticipated. Both a protective thickness of the potting material above the cable and a bed of the potting material thick enough to allow unhindered flexing of the cable must be provided. In addition, a rigid base must be provided for the transducer. On this basis, 1-1/2 inches (3.81 cm) appears to be about the minimum depth (L_D) possible for this transducer. A minimum slot width (L_B) appears to be 1-3/4 inches (4.45 cm). Estimated minimum slot dimensions would then be 1-3/4 inches (4.45 cm) x 1-1/2 inches (3.81 cm) x 42 inches (106.68 cm). The depth (L_D) could be substantially decreased if an extremely small cable can be fabricated with the proper characteristics. However, the width of the slot cannot be significantly decreased.

Some development work would be required to produce a usable transducer for this application. No evidence of the existence of an off-the-shelf transducer was found in this study. However, sufficient development has been done, as indicated above, to provide a firm basis for further developmental work, with only a minimal effort necessary to produce a usable transducer.

<u>Piezoelectric Crystals</u> - The use of Piezoelectric crystals is an intriguing possibility. The many and varied forms of geometry which are possible with these materials, as with semi-conductor materials, or combinations thereof, appear to be quite large. However, little work was uncovered during the course of this study in the use of these materials for measuring dynamic vehicle loads. One research effort in the

use of Piezoelectric crystals was conducted by McMaster and Rhoten at Ohio State University (15). Two transducers were constructed. The first counted trucks and the second was designed to weigh truck axles for further separation into four class intervals. These transducers were constructed of two pieces of angle iron with a spring-supported Piezoelectric crystal set between the pieces of angle iron. The transducer was then embedded in an expansion joint of a roadway. The use of these transducers also required the use of a vehicle separation sensor. Field testing of the first transducer was accomplished with encouraging results. However, further development work was required to achieve an adequately successful transducer. Only laboratory testing of the second transducer was achieved and substantial development work remained to be accomplished. Whether this work has continued to a more fruitful level was not determined from the literature search. No other research efforts were identified in the use of Piezoelectric crystals as compression-type "in-motion" sensors. As a result, available evidence indicates that a transducer development effort would be required in order to utilize Piezoelectric crystal technology in a compressive-type "in-motion" weighing system for bridges. The potential for developing usable transducers is quite large.

A candidate transducer using Piezoelectric material could be developed in the same form as the magnetostrictive cable transducer. The exterior appearance and dimensions could be exactly the same as for the magnetostrictive transducer (Figure 13). In place of the strain-sensitive cable, a bar of strain-sensitive Piezoelectric material would be used. Otherwise, the Piezoelectric transducer would be identical to

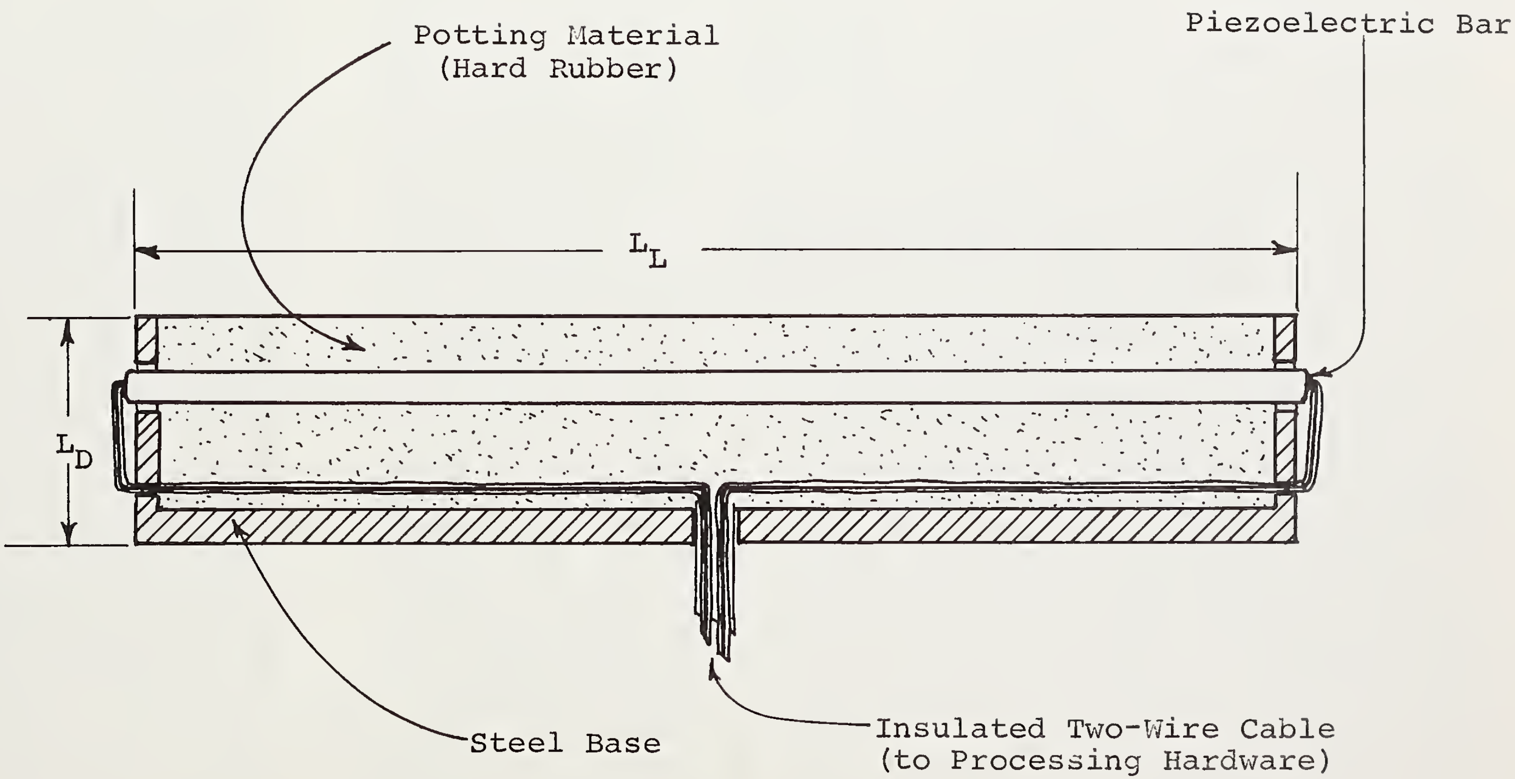


Figure 13. Piezoelectric transducer.

the magnetostrictive transducer. It would be installed and would operate in the same manner as the magnetostrictive transducer. The interface to the processing hardware would probably be different because of the different electrical characteristics and responses of the two transducers.

This transducer design requires a slot in the concrete deck of nearly the same dimensions as the magnetostrictive transducer. The Piezoelectric bar thickness is variable to some extent, depending on its material and its fabrication. Minimum possible dimensions appear to be:

$$L_L = 42 \text{ inches } (106.68 \text{ cm})$$

$$L_D = 1\text{-}1/4 \text{ inches } (3.17 \text{ cm})$$

$$L_B = 1\text{-}1/2 \text{ inches } (3.81 \text{ cm}).$$

As in the case of the magnetostrictive transducer, if a very small diameter Piezoelectric bar can be fabricated with proper characteristics, the depth (L_D) can be significantly decreased. However, the width (L_B) cannot be significantly decreased.

It must be understood that some developmental work would be required in order to provide a Piezoelectric type of transducer. The effort and cost required appears to be greater than that necessary for the magnetostrictive transducer.

<u>In-Series Load Cell</u> - Based on the work performed by Bourland, <u>et al.</u>(16), at the University of Michigan in developing a "cord load transducer," a similar potential transducer appears feasible for measuring "in-motion" dynamic loads. The

transducer developed by Bourland, et al., was specifically for determing dynamic cord loads in tires (Figure 14).

Using the same concept, a similar type of device can be developed and fabricated in the same transducer configuration as previously described for the magnetostrictive and Piezoelectric forms (Figure 15). Strain gages would be fastened into the center section of a moderately heavy metal rod or cable, which would be rigidly secured to the transducer end support. The basic transducer would then be packaged in the same manner as the magnetostrictive and Piezoelectric transducers.

This transducer design, as for the two previous designs, requires a slot to be cut in the concrete deck. However, the design that this transducer is predicated upon had an outside diameter of .0402 inch (.1021 cm). A more rugged transducer would be necessary for this application. However, an outside diameter between .1 inch (.254 cm) and .25 inch (.63 cm) appears possible. This would allow approximate slot dimensions of:

L_L = 42 inches (106.68 cm)

L_D = 1 inch (2.54 cm)

L_B = 1-1/4 inches (3.17 cm).

A minimum depth of 3/4 inch (1.9 cm) appears to be possible. Such dimensions provide a strong attraction to this transducer design.

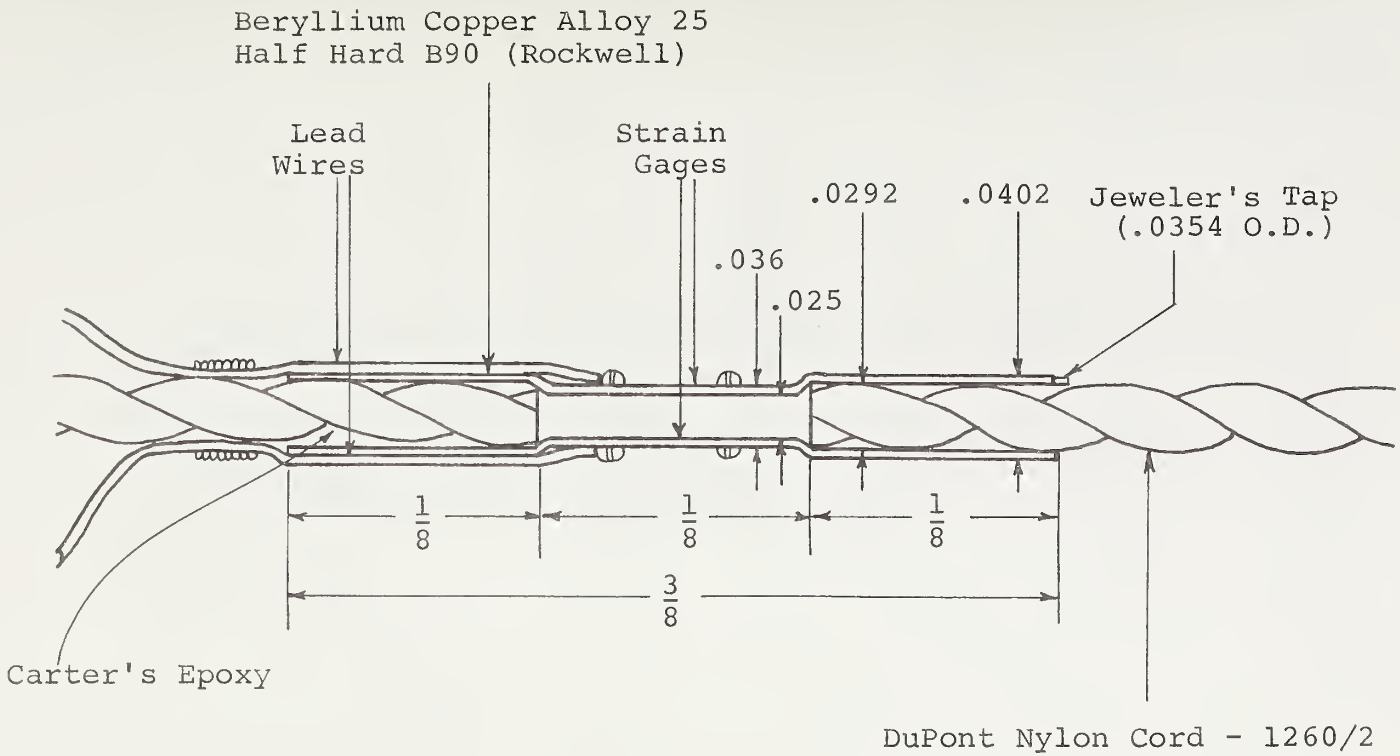


Figure 14. Cord load transducer (16).

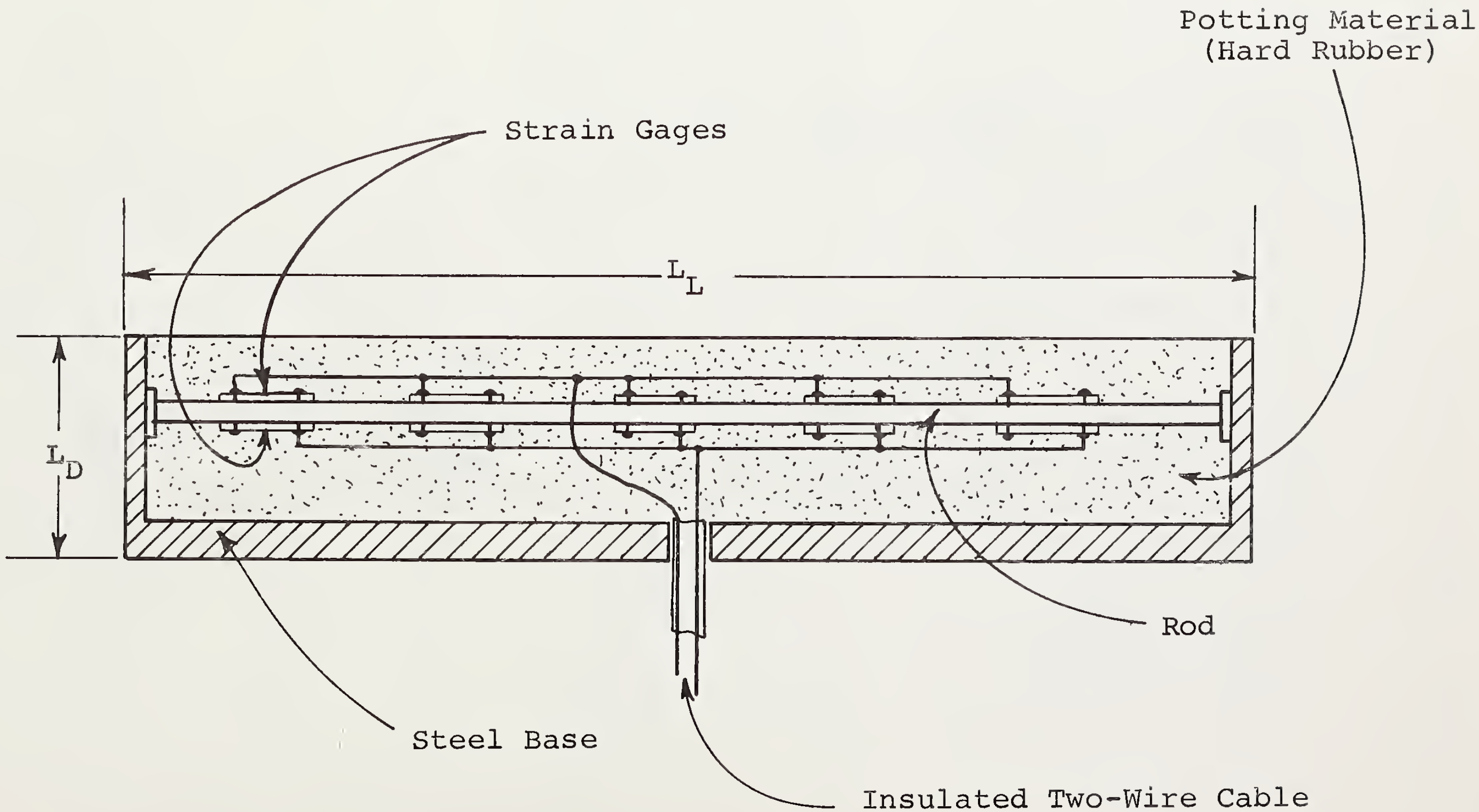


Figure 15. In-series load cell.

Although the development of such a transducer appears feasible, no such transducer has been developed for the type of use necessary to this application. However, the concept has been demonstrated for a different application. Therefore, a transducer development effort would be required. It would require about the same level of effort as for the Piezoelectric transducer.

<u>Exotic Elastomers and Plastics</u> - A serious attempt was made by the investigators to identify pressure-sensitive elastomers and plastics which could be formed as thin sheets or film. If such materials could be identified, they would lend themselves to deck surface installation with direct wheel contact, and yet would not require embedding in the bridge deck. These would be produced in strips or sheets a few microns thick, if possible. However, very little was found in the literature on such materials.

An investigation by Stanford Research Institute (SRI) (17) evaluated new forms of sensors, thin-film polymers and Nematic Liquid Crystals, and the use of combined sensors to eliminate false alarms.

One polymer, Polyvinylidene, in a thin-film form, .2734 x 10^{-6}-inches (11-microns) thick, showed excellent potential as an IR sensor. However, it was extremely sensitive to vibrational effects, including those generated by atmospheric acoustic pressure. Techniques of utilization were hypothesized which appeared to provide a solution to this problem. There did not appear to be any immediate means of exploiting this material for the purposes of this study.

ISI has been conducting some work in the use of temperature-sensitive Nematic Liquid Crystals for the past year and was familiar with the concept of Nematic Liquid Crystals such as were investigated by SRI. The Nematic Liquid Crystals sought in the investigation by SRI were to be pressure-sensitive so that potentially they could be used as a thin film in a direct-contact manner to measure pressure. However, presently, there is no direct means of obtaining a measurable signal from these materials. Further, the work performed by SRI on the pressure-sensitive materials and that performed by ISI on temperature-sensitive materials indicates that the response time of Nematic Liquid Crystals is far too slow for the purposes of measuring in-motion vehicle loads.

Two resistance-type elastomers were identified during this effort which show definite promise. These are discussed later in this section.

While this report was in final preparation, additional information was received on some other similar materials. This information had been requested from commercial sources at the beginning of the project. Unfortunately, there was no time available to evaluate these materials upon their receipt or to include such an evaluation in this report.

Conductomer - A pressure-sensitive elastomeric transducer (12) was developed by Nelson Crites, formerly of Battelle Columbus. The material used can be of different forms, such as silicone rubber and polyurethane foam. It responds to pressure by changing resistance. It varies from 1 ohm to 1×10^6 ohms in resistance. A particulate, such as carbon, is suspended within the foam. Expansion or compression

changes the distance between the particles, thus changing the resistance of the material. Polyurethane foam demonstrated a significant hysterisis. The foamed material is coated with a highly conductive rubber coating.

Presently, the patent rights are held by Scientific Advances, but no facilities exist for producing the material at present, nor have they existed for the past two or three years. A means does exist to produce small quantities of the material through Mr. Crites and Battelle Columbus using the laboratory facilities that were used during the development of the material.

The accuracy of the material increases as it becomes thicker in the direction of the load. If the material is allowed to remain under a load for approximately 48 hr, a permanent hysterisis occurs which makes it necessary to recalibrate the transducer. No specific evidence of its cyclic durability was determined. However, it was anticipated by its developers to be able to withstand millions of cycles.

From the identified characteristics of Conductomer, it appears to provide a feasible basis for the development of at least two forms of direct-contact, in-motion load transducers for bridge decks. The same transducer configuration could be used as was previously described for the magnetostrictive, Piezoelectric, and in-series load cell transducers (Figure 16). However, an additional form appears to be feasible, but may not be as accurate. This would be in the form of a thin pad which could be bonded directly to the surface of the deck.

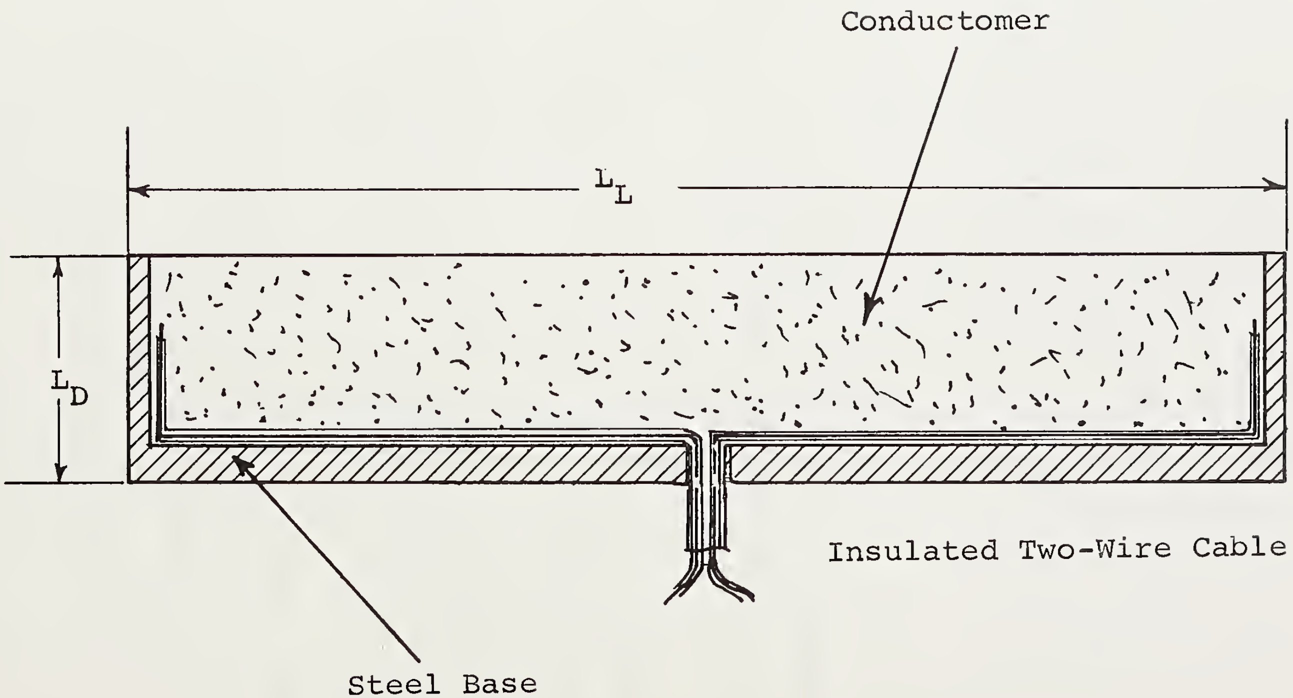


Figure 16. Conductomer transducer - type I.

In either case, no testing of this material has been made for the in-motion load measuring of vehicles. A development and testing program would be required before a usable transducer could be anticipated. Because of the nature of the basic transducer material, i.e., lack of experience in its use, the effort can be anticipated to be about the same as for the in-series load cell transducer of the same form. Casting this material into thin-pad transducers and testing this form of transducer appears to require a large effort. Two serious problems must be overcome for this form of transducer, i.e.:

1. Determining the minimum thickness and width necessary to achieve satisfactory load accuracy and not perturb the vehicle's dynamic behavior

2. Achieving an operationally sound transducer for deck surface installation, i.e., such that it will remain bonded to the deck surface.

These two problems do not exist in the first type of transducer configuration.

The transducer design illustrated in Figure 16 requires, as in the previous designs, a slot in the deck. Approximate slot dimensions are estimated to be:

L_L = 42 inches (106.68 cm)

L_D = 1 inch (2.54 cm)

L_B = 1-1/4 inches (3.17 cm).

Some variation in the depth may occur because of the uncertainty about the thickness of the material needed.

In the case of the thin-pad-type transducer design, the necessary thickness of the elastomer is of serious import to the successful development of this design, but has the same uncertainty problem regarding the thickness. Additionally, the perturbational effect of the pad on a vehicle's dynamic load function is dependent on the pad thickness. The possibility of fabricating a thin pad of this elastomer with a thickness of less than 1/16 inch (.16 cm) with adequate sensitivity cannot be predicted at this time. If individual pads exceed 1/16 inch (.16 cm), they should not be installed individually because they will act as significant and regular perturbations on the dynamic load function. In order to avoid such a condition, an installation process which will provide a smooth surface from approximately 35 ft (10.67 m) in front of the first transducer to the last transducer must be used. One such process would be to insert the transducer pads into a larger pad of a potting material that can be bonded to the deck surface.

Silicone Rubber - During the course of this study, the investigators carried out some independent tests of a commercially available silicone rubber product. This material was only available in thin sheets. In order to determine if the material would behave in a manner similar to the previously discussed Conductomer, several sheets were laminated together. Rudimentary tests of the pressure sensitivity of the material were made. It demonstrated pressure-resistance behavior similar to that reported for Conductomer.

The geometric dimensions of both possible transducers, the installation considerations, and the uncertainties concerning the necessary thickness of this elastomer are essentially the same as for Conductomer. From the limited data presently available, the thin-pad form of transducer would probably exceed 1/16 inch (.16 cm), but be less than 1/2 inch (1.27 cm).

Responses to inquiries directed to the manufacturer indicated that they were aware that the material was pressure-sensitive, but that no testing or evaluation of this property had been made. In terms of developing a transducer from this material, the same forms of transducers previously discussed for Conductomer are possible with this material. The effort and cost involved in developing either or both forms of transducers from this material should be somewhat less than that necessary for use of Conductomer, since this material is presently being produced in a commercial form.

Capacitance Sensor - The concept of developing a very thin capacitance pad appears to be an attractive means for acquiring dynamic axle loads. However, only two efforts were identified as having performed relevant research and development. One of these was in Australia. However, no data on this effort was retrieved during the literature survey phase of this study. The other effort was performed by the Tellurometer Division of Plessey Electronics Corporation (18) more than three years ago.

The device developed by the Tellurometer Division was a large capacitor with a rubber-air dielectric fabricated from a rubber pad with two layers of wire conductors, 19 inches (48.26 cm) x 72 inches (182.88 cm) x .3 inch (.76 cm).

It reportedly could be installed in less than 1 hr by two technicians. It was bonded to the road surface with asphalt and extended above the surface of the road only .3 inch (.76 cm). In tests, there was no loosening of the bonding after 10,000 axle passages. It was also easily removed. It was battery-powered and would operate unattended.

Compression of the dialectric produced a voltage pulse which was classified within one of 11 class intervals and was recorded in a weight class interval. It provided a total of 11 class intervals over a 0-to-40,000-lb (18,143.7-kg) weight range/wheel. This was an average of 3,600 lb (1,632.9 kg) per class interval, or a 3,600-lb (1,632.9-kg) resolution. It was 6-ft (1.529-m) wide and read only one side of an axle. It was reportedly satisfactory for single axles from 3 to 140 mph (4.83 to 224.26 km/hr) and for tandem axles from 3 to 60 mph (4.83 to 96.54 km/hr).

The development of a capacitance-type sensor in either of the previously discussed forms, i.e., the magnetostrictive cable geometric form or the thin-pad form, appears feasible. There is no reason that a finer resolution cannot be achieved with such a sensor. It merely requires more hardware and more logic, given that the electrical response is well-behaved.

To produce a sensor of this type, in either transducer form, would be roughly equivalent to the development of the in-series load cell, for each transducer form.

The Tellurometer Division manufactured two such devices (18). One was purchased and tested by the State of New York. The

conclusion drawn by the evaluation team was that the accuracy of the device was adequate for survey work and that the variations of the measured weight from the applied weight was less than 5 percent overall. Changes in speed appeared to seriously affect accuracy.

It is apparent that the resolution of the device was unsatisfactory for acquisition of weight data for law enforcement purposes. Further, the developers and the evaluators apparently failed to understand that they were dealing with a vehicle's dynamic load function. If several of the sensors had been installed in an array, as was done by Al-Rashid, et al. (5), and if the dynamic data had been reduced properly, much better behavior of the sensors would have been evident and the static weight determination, vehicle by vehicle, would have favorably improved, provided better initial resolution had existed.

The capacitance-type sensor appears very attractive based on the geometric dimensions possible. For the embedded-type transducers, similar to the magnetostrictive design, approximate dimensions possible appear to be:

L_L = 42 inches (106.68 cm)

L_D = .9 inch (2.29 cm)

L_B = 1-1/4 inches (3.17 cm).

The thin-pad-type design appears to be very attractive. However, the thickness of the protective exterior layers which would be necessary would exceed 1/16 inch (.16 cm).

The thickness of the sensor is insignificant, compared to the thickness of the protective layers. Because of the perturbational effect that single installations of these transducers would cause, another form of installation is necessary. A form of installation which would provide a smooth surface before and between the transducers would be necessary.

In general, the capacitance-type transducer appears to be the most attractive of all of the transducer candidates.

Indirect Load Sensors - At least three general types of indirect sensing can be used on a bridge deck which provide information on a dynamic load induced on the bridge deck. These three forms of sensing are accomplished by:

1. Instrumenting the bridge deck and main beams with strain gages. Derivation of the imposed load is based on the use of calibrated response strain data for a given bridge.

2. Instrumenting the bridge deck with seismic sensors, e.g., seismometers and geophones. At least one method of derivation of the imposed load is by similar reduction from calibrated data for a given bridge.

3. Instrumenting the bridge deck and beams with accelerometers.

The use of accelerometers was not seriously investigated in this study, since it requires a well-defined prior knowledge of the bridge's dynamic response for all vehicle loads at all

speeds possible. This problem, i.e., describing the bridge's dynamic behavior inversely to determine the dynamic force imposed by vehicles which develop the sampled accelerations, is nontrivial. In addition to this difficulty, the problem of treating multiple vehicle loads on a deck exists, which is also a nontrivial problem that does not lend itself to straightforward solution. As a result of the complexity and indirectness involved in the use of an accelerometer on a bridge deck to determine vehicle dynamic loads, no significant investigation of this approach was performed during the course of this investigation.

It should be noted that the problem of extracting multiple vehicle loads also exists in the signals acquired in the first two forms of sensing, as well as with accelerometer signals.

As was indicated earlier, the use of the first form of indirect sensing was not within the scope of this particular study. This reduced the indirect forms of sensing investigated to seismic sensing.

No use of seismic techniques to sense imposed loads on bridge decks was found in the literature survey. The use of seismic techniques on bridges appeared to be limited to acquiring elastic wave velocity for the estimation of Young's Modulus, for the concrete, and estimating deterioration and delamination (29) from seismic wave velocities, e.g., compression and shear. If the literature survey is representative of the limited use of seismic sensors on bridge decks, it would appear that the recent experimental tests performed by these investigators, in an independent effort, may be the first

attempt to sample the effects of dynamic truck loads using seismic sensors.

The use of seismic sensors for sampling dynamic vehicle loads on highways was performed by the U.S. Army (19) and by highway engineers in evaluating the effects of dynamic loadings on streets to nearby structures (20). Research previously performed for military purposes indicates that the use of passive seismic sensors to collect dynamic vehicle load data is feasible.

As indicated above, no direct research was uncovered on the use of seismometers of geophones in acquiring highway traffic data other than that performed by DOD in its use of these devices for intrusion detection. Consequently, the available experimental data that provides insight into the use of such sensors for measuring the dynamic loads of trucks on bridges is very limited. Most of the experimental work was primarily directed toward:

1. Intrusion detection, presence of foreign bodies ranging from a person to heavy tanks

2. Establishment of the range of an intruder

3. Establishment of the azimuth of an intruder

4. Establishment of the classification of an intruder.

In general, it appears that there has been no exploitation of the use of seismic energy to collect dynamic vehicle data. Studies such as the one performed by Texas

Instruments (1) do not do much toward increasing our knowledge in this area. Seismic sensors were summarily and inadequately treated in this work. Although this study was perported to be comprehensive and detailed, it fell far short of its goal in this area.

The uncertainties encountered in the results obtained in the intrusion studies (19), (21), (22), (23), (24) are due almost totally to the unknown characteristics of the geologic setting. This factor was dominant in the characterization of the received signal, since the energy source was usually significantly remote to the receiver, and the intervening geologic media composition and the moisture content were varied and unknown. This caused attenuating of the signal in an unpredictable manner for a noncalibrated range. Two techniques which have been evaluated in experimental tests can be used to eliminate this problem:

1. Pre-calibration of the geologic setting

2. Use of multiple sensors to simultaneously eliminate the unknown factors.

Studies sponsored by Fort Monmouth (25) investigated and compared the results of three forms of "seismic fences." These were structured about the use of:

1. Pulse seismic detection

2. Continuous seismic wave (CSW) detection

3. Passive seismic detection.

In the cases of the pulse and CSW seismic detection systems, a synthetic energy source is used to generate a seismic signal and an analogous electronic signal. The electronic signal is transmitted to a receiver and to a processor that compares the generated signal, which is represented by the received electronic signal, and the actual seismic signal received by the seismometer. The results of the experiment indicated that the pulse technique and phase-shifting evaluation using the CSW technique were not suitable. However, a frequency/amplitude modulation technique used with the CSW system and the passive system provided excellent results. These results, combined with those of other seismic vehicle detector experiments, indicate the feasibility of using such devices in acquiring dynamic vehicle-load-related data.

The amplitude of a seismic signal contains a multiplicity of parameters which prohibits the direct determination of the applied load from the sensor. These parameters are:

1. Distance of the seismometer from the vehicle

2. Weight of the vehicle

3. Number and spacing of wheels

4. Speed of the vehicle

5. Surface over which the vehicle is traveling

6. Geologic setting (bridge deck characteristics).

It is interesting to note that, during the course of the study, concern was evidenced over the interest of these investigators in the use of seismic data to determine the weight of vehicles in motion because of the existence of the above factors in the seismic signal. However, such concern was ill-founded, because these factors are components of the vehicle's dynamic load function which is imposed on a bridge deck, and it is the dynamic load which is being measured while a vehicle is in motion, not the static weight. If a sufficiently accurate representation of a vehicle's dynamic load function can be obtained, the static weight can be estimated with nearly the same accuracy. Further, these same factors exist in samples acquired from a direct form of sensor.

In order to determine the dynamic load of a vehicle, all of the dynamic factors must be either independently determined or held constant. The surface of a given bridge deck, except for winter snow and ice, is reasonably constant in seismic characteristics, and has a relatively smooth surface, as compared to a gravel roadbed. Similarly, the geologic setting, the bridge deck, is very dense, as compared to soil, and would be constant for a given bridge. These two factors would require calibration in order to obtain load data. A rough bridge deck surface could cause an increase in peak amplitude of a vehicle signal. The distance and speed of a vehicle can be determined by independent sensors, e.g., Doppler radar, Doppler sonics, range rate data, etc.

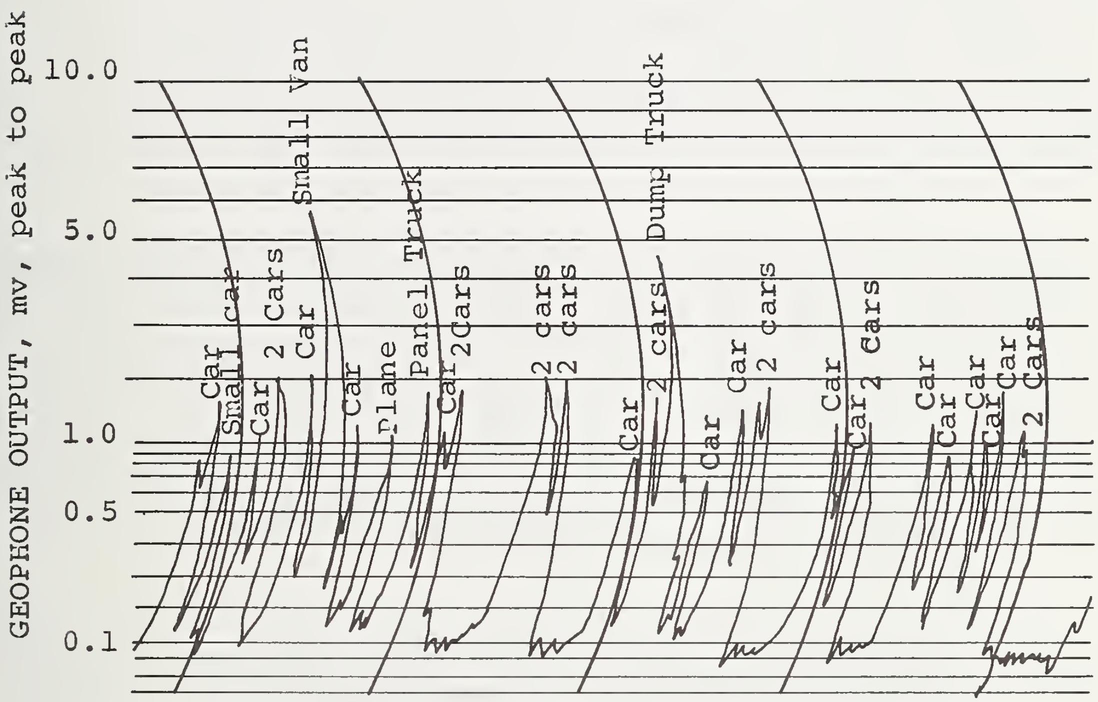
The determination of the number of wheels and their spacing is a more difficult problem, but can be managed with various sensors.

Hence, all of the dynamic factors can be independetly determined and the dynamic load of a vehicle in motion on a bridge deck can be conceptually extracted from a seismic signal.

The amplitude of the seismic signal provides basic vehicle identification information. Tests indicate that the frequency data recorded by a seismometer does not usually provide significant identification information. In one study (19), frequency appeared to be relatively insensitive to changes in speed or geologic setting. In a few cases, the seismometer-recorded frequency data included discrete components which were engine firing rates in the range of 125 to 150 cps.

Significant variation between the peak amplitude of autos, small trucks, medium trucks, and large trucks has been observed, which implies that a reasonable resolution of weight classes was achieved (19) (Figure 17). This recording rate was not sufficiently fast to identify axle or wheel peaks. However, it should be noted that the peak amplitude of an auto moving at 30 mph (48.27 km/hr) could be the same as a larger vehicle moving at 10 mph (16.09 km/hr). In general, it is possible for different vehicles to give nearly the same peak amplitude under different conditions. However, another seismic signal characteristic, signal persistence, can be used to allow distinction between two different types of vehicles. The larger, heavier vehicle will produce a more persistent signal than the smaller vehicle.

Tests showed that significant increases in amplitude occur between 10 and 20 mph (16.09 and 32.18 km/hr), but they also indicated that no significant increase in amplitude occurs above 35 mph (56.315 km/hr). However, these tests were



7 cps geophone, 15 ft. from road.
Car speeds averaged about 55 to 60 mph.

Figure 17. Levelmeter recording along an expressway (19).

conducted from 93 ft (28.35 m) to 1,000 ft (304.8 m) from the test vehicles. In the case of the bridge application, the seismometer will use the bridge deck as the geologic setting and will be very near to the source vehicles. Higher amplitudes, little attenuation, and good frequency resolution should be anticipated for the bridge application. However, much higher wave velocities should be anticipated in bridge decks over those found in the military experiments, i.e., 8,000 to 16,000 fps (2,438.4 to 4,876.8 m/sec) for the compression wave (26).

The pass band frequency data acquired in the military tests indicated that the frequencies were in the 0- to 150-cps range with most of the energy in the 1- to 20-cps range, and in a cylindrical wave form for distances above 93 ft (28.35 m) from the source. The military tests, through soil, indicated that attenuation was nearly linear from 200 ft (60.96 m) to 1,000 ft (304.8 m) from the source.

It was stated in one study (19) that individual vehicle detection by a seismometer can only be accomplished if either:

1. The density of the traffic is low and in a single file

2. It is supplemented by other sensors.

In addition to the military equipment tests, tests were made of civilian traffic at Ann Arbor, Michigan, and Hollister, California. Good distinction was observed between the various types of vehicles (Table 5). It was also observed that two similar vehicles passing simultaneously caused only a very slight increase in amplitude over that which would have been

expected for only one of the vehicles. Different sized vehicles passing together could be distinguished.

Table 5. Relative broad-band amplitudes.

Peak Signal (db)	Vehicle	Seismometer Distance (ft) (.30481 m/ft)	Average Speed (mph) (1.609 km/mile)
4 to 6	Automobiles	10 to 15	60
16 to 19	Large trucks	10 to 15	45
12 to 14	Medium trucks	10 to 15	50
-5 to -10	Automobiles	100	50
8 to 10	Large trucks	100	40
0 to 44	Medium trucks	100	45

The experimental and theoretical studies on the use of seismic sensors to collect vehicle data does not provide direct examples of axle load data or bridge use. In general, the recording devices which were used washed out the higher order effects from the dynamics developed by a vehicle. It is anticipated that a bridge deck will provide an excellent "geologic setting" and that the use of more sensitive and faster recording will provide sufficient signal detail to allow acquisition of dynamic-load-related data due to individual axles during their travel across the instrumented span. The lack of directly applicable information on the use of seismic sensors on bridge decks, and the lack of data to determine if the effect of individual axles was contained

in a vehicle's seismic signature, caused these investigators to perform some experimental work independent of this study in the use of seismic sensors on bridge decks.

The collected data was not fully analyzed at the time this report was prepared. Further, the recording sensitivity and speed used during the field work was borderline. The recording speed was almost too slow to observe the component detail which existed in the seismic signal. However, preliminary analysis of a few samples recorded at 25 mm per second on a Bush recorder indicates that axle peaks due to impact on entrance to the span were contained in the initial transient.

Axle frequency also appears to be contained in the recorded data; i.e., periodicity of peaks correlated with expected suspension system frequencies during the transit time of the axles was observed. Free period vibration of the bridge used in the test appeared to be on the order of 4 sec. Axle impacts on leaving the span also appear to correlate with the expected axle transit times.

In many of the seismic detection experiments, the investigators found some recorded seismic data containing pure seismic data and some containing seismic and acoustic signals. In some cases, the investigators were unclear as to the cause of the coupled acoustic-seismic signals. In one experiment, the use of microphones with the seismic sensor provided a pure acoustic signal that, in effect, reproduced the acoustic component of the seismic recording.

It appears that acoustic energy generated by a vehicle is directly transmitted into the roadway (or bridge deck) and

becomes coupled with the seismic energy unless attenuated by the geologic media. The absence of the acoustic signal in certain cases could be due to the existence of an acoustic insulator between the vehicle wheel and the geologic transmission media, rather than a selective attenuation of the acoustic component only. Also, inadequate insulation of the seismic sensor from the surrounding atmosphere could have allowed acoustic coupling with the atmospheric acoustic waves.

In those experiments which analyzed the acoustic component of the seismic recording and/or a pure acoustic signal, it was found that the acoustic component was primarily generated by the vehicle's engine. The engine firing frequency and rpm were filtered out of these recordings and clearly identified.

This determination leads to the possibility of extracting additional data, i.e., classification information, on vehicles that would at least reinforce presently collected classification data.

Measurements of bridge deck acoustic wave velocities range from 8,000 fps (2,438.4 m/sec) to 16,000 fps (4,876.8 m/sec) (26), depending on the quality and deterioration of the concrete. This definitely implies the need to acoustically calibrate a bridge deck before trying to utilize any acoustic signal acquired from it. It is assumed that the same tendency will occur with the acoustic wave as with the compression wave in reinforced concrete, i.e, the tendency to approach the acoustic speed of steel. Care must be exercised in installing seismic sensors to avoid ambiguities which could arise from the seismic wave traveling along the reinforcing steel rods.

Based on the results of Army tests of geophone behavior and detection response, the horizontal component of the compression wave appears to give the sharpest signal and the steepest rise and fall slopes, which are essential. Further, the vertical component will have the shortest path from the source to the receivers, but, because of the atmosphere interface above and below, only a portion of the wave will dissipate when contacting the atmosphere. It will then reflect from the outer wall, rebounding toward the opposite surface, i.e., from top surface to bottom surface of the deck and vice versa. This will create an even more complex receiver problem. Hence, it appears that the horizontal component is the best candidate. Some reflection of the horizontal wave can be anticipated from the sides and ends of the span, but should be less of a problem than that created by the vertical wave.

Seismic experiments (37) with a layer of ice under air and over water, an ice-covered lake, appear to be somewhat analogous to a concrete bridge deck over and under air. In these experiments, it appeared as if the ice layer acted as a transmission duct with some losses of signal to the air and water and some noise acquisition from them. The situation with a bridge deck appears to be very similar in terms of signal losses and noise contribution. It is also possible that the deck will transmit seismic waves in the manner of thin layers, i.e., ducted, depending on the surrounding environmental state and the condition of the deck concrete, especially in the case of delamination.

Noise acquisition should be primarily of an acoustic form and can be removed with filters. Because of some direct effect,

it is anticipated that very strong signals will be present, with a proportionate increase in the noise level.

The use of seismometers or geophones appears feasible, as stated earlier, for acquiring dynamic vehicle load seismic data. However, significant experimental work is required to provide a sound evaluation basis. The major difficulties arise in:

1. Defining precisely the properties of the seismic signature

2. Extracting specific axle signature data.

The isolation of specific vehicles in a multi-vehicle deck environment can be accomplished by the use of a lanal array of seismic sensors. Experimental results obtained by these investigators evidenced good lanal distinction. The use of longitudinal array should provide a basis for satisfactory longitudinal discernment.

In general, there is such a lack of experimental evidence in the use of seismic sensors on bridge decks that no firm decision can be made at this time whether their use is practically feasible or not. All available evidence is favorable, but not conclusive. In order to provide a decision basis, a comprehensive program of test and evaluation is necessary. It appears to these investigators that all of the instrumentation and hardware necessary, from sensor through recording to digital computer for data reduction, are readily available. No hardware development program appears to be necessary to carry out such an investigation. Integration of

the supporting sensors which would be necessary in such an investigation would require some effort, but, again, off-the-shelf components are available. The performance of such an investigation would require supporting sensors to determine speed and axle position. The seismic experimental work performed by these investigators merely provided more stimuli to perform additional experimentation. As indicated above, some information was acquired that indicated that some anticipated problems were resolveable, e.g., discernment between multiple vehicles occupying a deck simultaneously, and apparent identification of individual axles. However, the apparent information content was much larger than expected and stimulated more interest in what was contained, and how to extract and identify it.

Installation Considerations

Preliminary calibration of a bridge will be an absolute necessity for either the direct or indirect form of acquisition system. For the direct form of acquisition, it will be essential that road roughness profiles be taken from the entrance roadway for some significant distance, and from each lane of the bridge deck through the proposed sampling area. Analysis of the profiles should be made on the basis of the types of trucks that can be anticipated in the population and the speed envelopes within which each type will be contained. This analysis would provide a basis for determining the installation locations and the number of installations necessary. Such an analysis can be performed by using a pavement load prediction computer program such as described in the work of Al-Rashid, et al. (5). Such a process could be established in a routine operational manner to provide installation requirements for any given highway bridge. This calibration

becomes of even more importance for highway bridges with long free vibration periods and subject to long queues of heavy trucks which cause repeated resonant loadings, as discussed by Karrh and Douglas (27).

For the indirect form of acquisition, the dynamic calibration process defined for the direct form would be valuable in characterizing the vehicle signatures that would be acquired. However, the indirect form will require additional calibration over the direct form. Specifically, pre-calibration of a bridge deck can be easily accomplished using techniques already in existence and presently used to determine the condition of a bridge deck, e.g.:

1. The delamination test

2. In-situ strength tests using the acoustic pulse technique

3. Soniscope test.

The delamination, acoustic, and soniscope tests provide means to directly determine the velocities of the various seismic waves, compression, shear, etc. These are not an all-inclusive set of existing techniques (26), (28), (29) which could be used to calibrate a bridge deck in terms of seismic and acoustic properties. However, they provide a significant starting point.

Measurements of the velocity of the compressional wave in concrete range from 8,000 to 16,000 fps (2,438.4 to 4,876.8 m/sec).

This implies the need to pre-calibrate a bridge deck before using acquired seismic data. This variance also holds true for the shear wave. The compression wave tended toward the velocity of steel, 16,732 fps (5,099.9 m/sec), in reinforced concrete bridge decks. Several concrete bridge decks, in addition to many laboratory samples, were tested in this study (30).

If a bridge deck has been overlayed with asphalt pavement, micro-seismic techniques (31) can be used to calibrate both the asphalt pavement and the deck concrete.

Depending on the data-reduction process used on the seismic data, it may be necessary to pre-calibrate the portion of each highway bridge that is seismically instrumented with a set of trucks with static loads at speeds sufficient to provide a signature analysis basis.

In both cases, direct and indirect, it must be remembered that the roadway surface entering the bridge will undergo time-dependent changes. Long-term use of an "in-motion" weighing system will require periodic road roughness calibration.

At present, the most practical way to utilize seismic sensors to acquire dynamic load data is to pre-calibrate the bridge deck from a known load, i.e., to effectively establish a signature library. This data could then be used to identify the collected seismic signature by direct or by interpolative signature analysis.

The actual installation of a seismic sensor requires that it be well insulated from all surrounding media except the media to which it should be coupled, e.g., in the case of sensing a bridge deck, from air-coupled acoustic waves. Similarly, electromagnetic shielding of the seismic sensors is necessary. Such interference can be encountered which is high enough to mask the signal.

Supporting Sensors

The purpose of this subsection is to present an evaluation of the available support sensors, as shown in Table 3, in terms of the requirements of this application.

Neither the direct nor the indirect forms of sensors presently available are capable of singly acquiring all of the variables required in the minimum essential set of variables. As indicated earlier in the requirements discussion, the direct form requires at least a supporting sensor capable of definitely distinguishing between vehicles, i.e., a passage detector. If only a single-sensor installation is used, the direct form also requires a speed-detecting sensor. However, for multiple installations with a synchronized electronic clock, the speed of a vehicle can be determined from axle arrival times at each load sensor.

The indirect form, i.e., the seismic sensor, can almost distinguish between vehicles and axles. Further, some indication of a vehicle's speed can also be determined from the acquired signal. However, none of this information can be extracted with a great deal of certainty at this time.

Consequently, a supporting sensor(s) capable of definitely distinguishing between vehicles and detecting vehicle speed is necessary. If axle data cannot be extracted with a high degree of certainty, an axle detector is also necessary to support the indirect form of load sensor.

A bridge deck has a unique characteristic that is not found in highways and, consequently, has never been exploited in terms of its advantages in collecting traffic data. The highway engineer must either embed his traffic sensors in the pavement or mount them in a sidefire or overhead position.

However, in order to collect pavement behavior data, e.g., deflection, strain, etc., the highway engineer has had to resort to indirect techniques. However, the bridge engineer has, from the time he understood structural analysis concepts, been able to measure structural behavior directly from his bridge by taking his measurements from beneath the bridge deck and from the beams. However, he has traditionally been behind the times in collecting information about the traffic which uses his bridge. It would be very desirable to be able to develop an "in-motion" weighing and traffic data-collection system that could be mounted beneath the deck, similar to the manner in which bridge structural measurements are made. This severely constrains the possible support sensors which can be used. For those support sensors which cannot be used from beneath the deck, surface, sidefire, or overhead installations are the only installation alternatives. Neither the sidefire nor overhead alternative is really desirable unless an already existing structure can be used for mounting the sensors.

Chemical Sensors - Chemical sensors have been shown (32) to be highly effective in sensing the presence of vehicles and, to some extent, in classifying them. However, the response time of such sensors, the difficulty in generating a recordable signal, and their extreme dependency on the wind's direction and speed make them completely unsuitable as candidates for vehicle passage or presence detection sensors for this application.

Optical - Within the optical category, we will treat infrared and photoelectric cells. Some success has been achieved in the past with the use of optical-type sensors. Substantial investigation of photoelectric cells was performed by Keith and Yan (33), with some success. However, in at least two investigations by Minor (34) and Ameigh, et al. (2), it was indicated that environmental factors seriously inhibited the effective use of optical-type sensors. The effectiveness of induction loops, magnetic detectors, radar sensors, and untrasonic sensors far exceeded the abilities of the optical-type sensors.

Acoustic Sensing - The use of highly directional microphones appear to be a possible means of distinguishing between vehicles and identifying axles. No specific test of such a concept was found during the literature survey.

Military intrusion tests (19), (21) indicate that the acoustic component extracted from a seismic signal was primarily generated by a vehicle's engine. The engine firing frequency and rpm were filtered out of these signals and clearly identified. It would appear that the use of directional microphones would greatly enhance the acquisition of vehicle

acoustic signatures.

Other classification data that can be potentially extractable from seismic-acoustic or pure acoustic data from highly directional microphones are:

1. Type/class of vehicle (reinforcement, at least)

2. Incidence of type class occurrance

3. Engine classification (indirectly, engine power data).

It appears possible to use highly directional microphones to acquire tire noise signals. Such information could be used in obtaining the axle data necessary, and, possibly, other vehicle classification data desirable from tire noise signatures.

The Doppler effect has been observed (21) in the acoustic coupled signal in seismic data, but was of such low resolution that it could not be used for vehicle speed prediction. In considering this finding, it should be noted that such data was acquired over long distances through varying geological media and does not necessarily correspond to the behavior which would be encountered in the use of directional microphones. However, the state-of-the-art is such that much uncertainty exists in the practical use of this sensor. Other proven sensors are available and their performance characteristics are well known. Advancement of the state-of-the-art in vehicle detection and classification will probably remain with the military until a usable, at least for evaluation,

sensor system is available.

The use of this sensor is not recommended due to the development work necessary before it can be evaluated and the availability of other proven sensors.

Video - Video detectors have been tested and used in traffic surveillance systems (2) and in tunnel surveillance systems. They have not been used, in general, as discrete event detectors, such as the detection of an individual vehicle. They are extremely expensive, especially in reducing the acquired two-dimensional signal, and they are dependent upon available light levels. Low-light-level video equipment has been produced (35) for real-time monitoring, with the following characteristics:

1. Weatherproof enclosures

2. Illumination ranges of 1 to 100,000,000

3. Fixed focal length or 10:1 zoom

4. Remote-control panel

5. Shading correction over a $\pm$6-v range

6. Automatic dark current correction

7. Automatic light control/automatic iris

8. Horizontal scanning at 525 lines/frame

9. Vertical scanning of 30 frames/second.

Such characteristics provide a powerful video scanning capability.

In considering such sensors for the "in-motion" weighing system, it is obvious that they can only be mounted within optical view of the bridge traffic. This implies the need for either sidefire or overhead mounting. They also will be in direct view of the vehicle operators, which is not a desirable feature. Consequently, the use of video scanners as support sensors is not recommended for use in this system.

Laser Radar - No research or developmental work on the use of laser radar was identified in the literature survey phase of this project. However, these investigators had knowledge of the laser range-finder devices used by the U.S. Army's artillery, and the developmental work presently underway for an infantry mortar laser range-finder. No immediately available laser sensor was identified which could be used effectively by this system. Further, the optical view requirement exists with lasers, as with the video scanner, which is an undesirable characteristic in the support sensor. As a result, laser radar devices were eliminated from consideration.

Ultrasonic Sensors - Ultrasonic sensors have proven to be very effective, economical, and reliable as traffic sensors. However, the motion detection form, CW-Doppler, reportedly (2) has a higher accuracy in presence/passage detection than does the pulsed form. Both forms of the ultrasonic sensors must be mounted above the bridge deck, not necessarily in direct optical view of a vehicle operator, but in such a way as to have a line-of-sight position to the vehicle, e.g.,

directed downward from a mounting behind an overhead road sign. Both forms also provide discernment of vehicle separation. For an above-the-deck mounting, the ultrasonic (CW-Doppler) sensor is considered a satisfactory candidate for the Passage-Velocity-Detector (PVD). The pulsed sonic detector does not provide speed detection and is not a suitable sensor for this system.

Induction Loops - RF loops are also well-proven traffic sensors. They are also one of the most economical sensors available. The installation time and cost for this sensor is among the lowest of all of the available traffic sensors. However, a single loop will not provide speed data. Multiple loops must be used in order to estimate a vehicle's speed. For the determination of vehicle passage only, the induction loop is a satisfactory sensor candidate. The use of multiple RF loops to estimate speed and vehicle passage would provide a feasibly satisfactory PVD for this system, except that it must be supplemented by a sensor capable of discerning vehicle separation.

Magnetic Transducers - There are numerous forms of magnetometers (Table 3), some of which have been used, or tested, in traffic sensing applications. In general, these sensors provide presence or passage information. Some signal signature value exists for possible classification use. Some hypothesis exists for extracting speed from the acquired vehicle passage signature (2). However, difficulties exist in extracting this variable from the signal. The cost of these sensors is low, but somewhat more than the cost of induction loops. Speed data could, again, be determined from

a multiple sensor array in each lane. It should be noted that difficulties have arisen in the use of magnetometers in multi-lane highways.

In addition to magnetometers, a recent program by the FHWA has led to the development of the Magnetic Gradient Vehicle Detector (MGVD) (36). It, again, is a sensor which must be embedded in a road surface or bridge deck. However, it requires only a small straight slot. It does not directly acquire speed; however, there is some evidence that vehicle speed may be derived from the acquired signal. It apparently does not have serious multi-lane use problems, as in the case of magnetometers. Multiple installations would be required to provide, with certainty, vehicle speed, and such an installation would provide a satisfactory PVD for this system.

Radar - The CW-Doppler, as a single sensor unit, provides determination of vehicle passage, separation, and speed. More importantly, it is the only sensor that can be installed beneath the deck and still collect the necessary data. Installation is easily performed and does not interrupt traffic. However, an installation that is made any significant distance from the ends of the bridge will require some form of platform on which the installation crew can stand. This sensor should be installed in a manner that produces minimal or no radiation reflection from the reinforcing steel in the deck. A single bar in the antenna path will not significantly affect the return signal. Present costs of such sensors are economically competitive. If combined with an indirect form of dynamic load sensor, the entire sensor package can be installed beneath a bridge deck, which is

extremely desirable. CW-Doppler radar sensors fully satisfy the support sensor requirements for this system.

Comparative Analysis of Sensing Systems

Because it was possible to define a "universal" or common acquisition system and reduction process for compressive-type sensors, and because of the uncertainties involved in the data-reduction process, no actual system comparison is necessary. However, a comparison of the direct forms of load sensing transducers and potential PVD's is necessary.

Two conceptual designs of compressive-type transducers were developed during this study. The first was generated to provide a common geometric configuration which will be referred to in this report as the "universal transducer design." The second design takes advantage of the ability of certain transducer materials to be formed as thin pads, and will be referred to as the "thin-pad design."

Load Sensors - Table 6 presents a tabulation of significant factors for each of the possible transducers, exclusive of cost. The cost differences are generated by the differences in cost for each of the transducers and for the necessary interface hardware to make the output from each transducer compatible to the input side of the processing hardware.

Exclusive of cost, a ranking of the compressive-type transducers, based on the content of Table 6, is as follows:

1. Capacitance sensor (thin-pad transducer design)

Table 6. Load sensor comparison.

Transducer	Development Ranking	Form of Installation	Advantages	Disadvantages
Magneto-strictive cable (universal transducer design)	1	Embedded in the deck in each lane	Ease of installation; Direct form of sampling; smallness of transducer; Rapid mechanical response; Minimal development; Prior use of similar transducer	Slotting of concrete deck; Transducer requires development
Piezo-electric crystals (universal transducer design)	2	Embedded in the deck in each lane	Ease of installation; Direct form of sampling; Smallness of transducer; Rapid mechanical response; Nominally small development	Slotting of concrete deck; Lack of experimental data on transducer; Transducer requires development
In-series load cell (universal transducer design)	2	Embedded in the deck in each lane	Same as Piezoelectric	Same as Piezoelectric

Table 6. Load sensor comparison (Continued).

Transducer	Development Ranking	Form of Installation	Advantages	Disadvantages
Conductomer (Elastomer) (universal transducer design)	2	Embedded in the deck in each lane	Ease of installation; Direct form of sampling; Smallness of transducer; Rapid mechanical response; Nominally small development	Slotting of concrete deck; Lack of experimental data on transducer; Transducer requires development; Acquisition of material may be difficult
Conductomer (Elastomer) (thin-pad transducer design)	2	Bonded to deck surface in each lane	Ease of installation; Direct form of sampling; Smallness of transducer; Rapid mechanical response; Moderate level of development	Lack of experimental data on transducer; Acquisition of material may be difficult; Thin layer may not provide sufficient resolution; transducer requires development
Silicone rubber (Elastomer) (universal transducer design)	2	Embedded in the deck in each lane	Same as Piezoelectric	Same as Piezoelectric

Table 6. Load sensor comparison (Continued).

Transducer	Development Ranking	Form of Installation	Advantages	Disadvantages
Silicone rubber (Elastomer) (thin-pad transducer design)	2	Bonded to deck surface in each lane	Same as Conductomer	Lack of experimental data on transducer; Thin layer may not provide sufficient resolution; Transducer requires development
Capacitance sensor (universal transducer design)	2	Embedded in the deck in each lane	Same as Piezoelectric	Lack of experimental data on this form of transducer geometry; Transducer requires development
Capacitance sensor (thin-pad transducer design)	1	Bonded to deck surface in each lane	Same as magnetostrictive cable	Transducer requires development
Seismic (seismometer or geophone.)	3	Fastened beneath deck under each lane	Ease of installation (no direct traffic contact); Rapid and sensitive response; Favorable evidence	Lack of conclusive evidence; Reduction of acquired data; Requires experimental evaluation; May require vehicle/axle position support sensor

2. Magnetostrictive cable sensor (universal transducer design)

3. Piezoelectric crystals (universal transducer design)

3. In-series load cell (universal transducer design)

3. Silicone rubber (universal transducer design)

3. Capacitance sensor (universal transducer design)

4. Conductomer (universal transducer design)

4. Silicone rubber (thin-pad transducer design)

5. Conductomer (thin-pad transducer design).

The estimated cost to produce a prototype of any one of the above transducers will be quite small.

Support Sensors (PVD) - Table 7 presents a tabulation of significant factors, including cost estimates for purchase and installation of single-lane sensor packages. The CW-Doppler under-deck radar PVD is the most attractive. Its estimated cost per lane is slightly more than the magnetometer package, which has some significant disadvantages. The induction loop and the MGVD are on a par in terms of cost. However, the induction loop is in production, whereas the MGVD is a recent development and it is understood by these investigators that it is not yet in production. Magnetometers are marginal because of their lane overlap problems.

Table 7. Candidate support sensor (PVD) comparison.

Sensor	Form of Installation	Advantages	Disadvantages	Sensor Purchase Cost	Installation Cost
Sonic (CW)	Overhead	Single sensor per lane; Vehicle separation; Can be shielded from driver view; Good lane discernment	Overhead mounting; Unobstructed line-of-site view; May interrupt traffic for installation	$1,000	Approx. $600 (if pole and base included)
Induction loops	Surface-embedded	Covert installation; Good lane discernment	No vehicle separation; At least two sensors required; Traffic interruption for installation	Approx. $600	Approx. $1,500
Magnetometers	Surface-embedded	Covert installation; Vehicle separation	At least two sensors required; Slight traffic interruption for installation; Multi-lane difficulties	$400	Approx. $200
MGVD	Surface-embedded	Covert installation; Fair lane discernment; Vehicle separation	At least two sensors; Traffic interruption for installation; Not yet in production	$400 (Estimated)	Approx. $1,500
Radar (CW-Doppler)	Beneath the deck	Covert installation; Single sensor; No traffic interruption for installation; Good lane discernment; Vehicle separation	Necessity of avoiding reinforced steel bars	Approx. $1,000	Approx. $700 (Bridge-dependent)

Sonic sensors are quite satisfactory except for their above-the-deck mounting requirement and their cost. If an overhead structure, such as an overhead road sign, already exists, and the sensors can be mounted out of the direct view of vehicle operators, they are quite satisfactory. Also, their installation costs will substantially decrease to a few hundred dollars if they can be installed on an existing overhead structure.

Assuming no existing overhead structure over that portion of a bridge deck which is to be instrumented, a ranking of the candidate PVD's is as follows:

1. Underdeck CW-Doppler radar

2. MGVD

3. Magnetometers

4. CW-Doppler sonic

5. Induction loops.

No development cost, as such, exists with any of the candidate sensors. Components or the entire sensor are available or can be produced.

DEFINITION OF ACQUISITION SYSTEM

The evaluation of the state-of-the-art in the use of the direct-contact form of load-sensing transducers and in the use of indirect seismic sensors for collecting dynamic truck axle load data indicated that:

1. The use of seismic sensors appears possible, but more experimentation and analysis must be performed to obtain conclusive evidence for a valid decision

2. The use of several forms of direct-contact sensors is feasible and within the present state-of-the-art.

As a result, only an acquisition system for the direct-contact form of dynamic-load-sensing transducer will be treated in this report.

Two basic philosophies exist in developing acquisition systems. The most common is to develop an acquisition system which is designed around the transducer and is highly efficient in processing and recording the information acquired by the transducer. This makes the acquisition system completely dependent on the electrical characteristics of the transducer and on the signal processor that was designed specifically for that transducer. In terms of a developmental effort or prototype development effort, this approach is an "all-your-eggs-in-one-basket" situation. If the

transducer does not perform satisfactorily, the specialized acquisition system is of no value, except for component salvage.

These investigators have used the second approach, which is to develop an acquisition system which is effectively independent of the transducer used as the sensor. This allows the acquisition system to be used as a means to either evaluate multiple transducers, or, if the best candidate fails to prove totally satisfactory, to test alternate candidates. This approach has a great deal of merit for the development of a prototype system. It provides an immense increase in the probability of the success of such an effort.

The hardware necessary to accomplish such an approach will increase slightly the cost of this acquisition system over that of the one-shot form. The actual increase occurs in the interface necessary for each transducer. The output side of each interface will be pluggable to the main acquisition system and have common electrical characteristics and signal format.

A system predicated on this second approach is conceptually defined within this section. However, all of the candidate transducers have not been treated. The capacitance-type sensor has been used as an example of the transducer hardware necessary to the system. The system described within this section is defined from the transducers to the recorder.

The universal transducer design, after installation, would be of the same nature as an induction loop; i.e., it would effectively be a semi-permanent installation (of the transducer only). The acquisition and recording system would be movable up to the connection to the transducer. It is estimated that the cost of removing the acquisition and reduction system would be about the same as the installation cost, except for the transducer installation costs.

This infers that the universal transducer must be, effectively, of a throw-away nature, and, consequently, must be of low cost. Present estimates of cost, depending on the specific transducer, when in production, range in the $35 to $75 price range. It should be noted that an actual "throw away" of these transducers does not really occur. They would be reusable; i.e., the acquisition and recording system could be reinstalled and the already-installed transducers would merely plug into the system. This concept is very attractive for new bridges; i.e., upon construction, the contractor would install the transducers in the deck with a plug-in ability to an acquisition and recording system. This same concept also is attractive in terms of strain sensing.

The thin-pad-type transducer could be either permanently bonded or fabricated in such a way as to allow easy removal and reuse, as for Tellurometer's weight analyzer.

In both cases, any overlaying of pavement over the sensors, as is done occasionally with asphaltic concrete, poses a

problem of unknown proportion to the ability of either transducer to continue to operate properly. If the course of pavement is thin, it is possible that sufficient load will be transmitted to the transducers; i.e., the pavement overlay would support only a small portion of the induced load. However, it would require recalibration of the transducers. If the overlayed pavement supported a large portion of the load, the transducers would tend to lose their sensitivity to variations in the loads, i.e., resolution. In this case, the transducers would require removal and reinstallation or abandonment and installation of new transducers.

Capacitor Weight Sensor

Of the several sensor types that show promise in the development of a universal sensor package, the "compressive capacitor" is the most versatile and can be implemented with the least development.

The proposed "capacity sensor" may be used in two forms:

1. Deck surface pad

2. Inset strip.

The surface pad is installed on the top surface of the bridge deck using a bonding agent, whereas the inset strip is constructed in the universal mount and inserted into a slot cut in the bridge deck. Both types of mounting involve the same electronic package (see Figure 18).

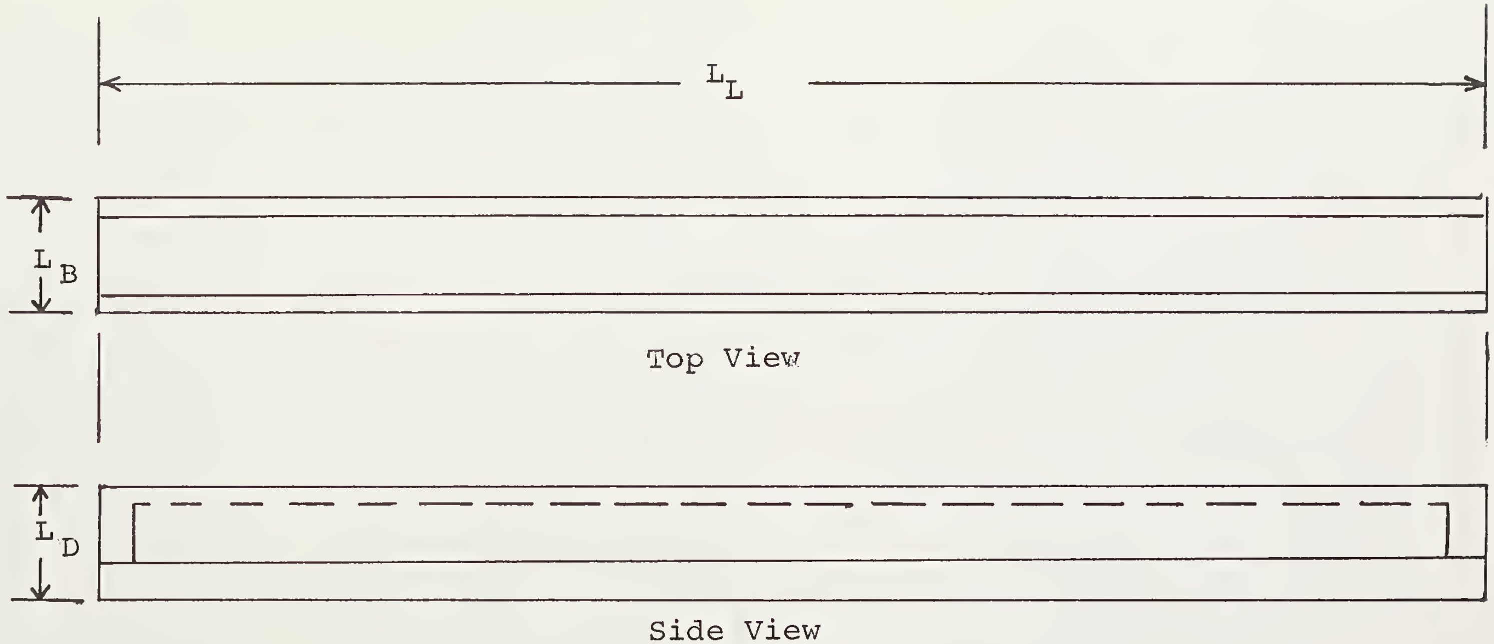


Figure 18. Standard embedded sensor package.

The capacitor pad is two plates of conducting material separated by an insulator. If the two plates are separated by a variable thickness dielectric, the capacitance will vary with thickness. An example of this is the old compression type of trimmer or tuning capacitor which used a dielectric of mica sheet between conducting plates (foil). The capacitance range of the capacitor was at least 10:1.

The capacitor pad is mounted in the universal package, as shown in Figure 18. The pad could also be designed for surface-mounting on the deck or roadbed as in the Plessey weighing device (18).

The proposed pad is composed of a group of plates (Figure 19) utilizing metal-plated mylar film. The mylar film was chosen for several reasons:

1. It is temperature-stable

2. It can be formed in very thin sheet thickness

3. It remains flexible.

The dielectric for the capacitor is air, but the spacing material is silicone rubber. The silicone rubber is a very thin sheet of about 10 mils thickness with a great number of large-diameter holes punched throughout the material (see Figure 20). The purposes of the air holes are:

1. Air is the dielectric instead of rubber

2. The holes enable the rubber stack to compress farther

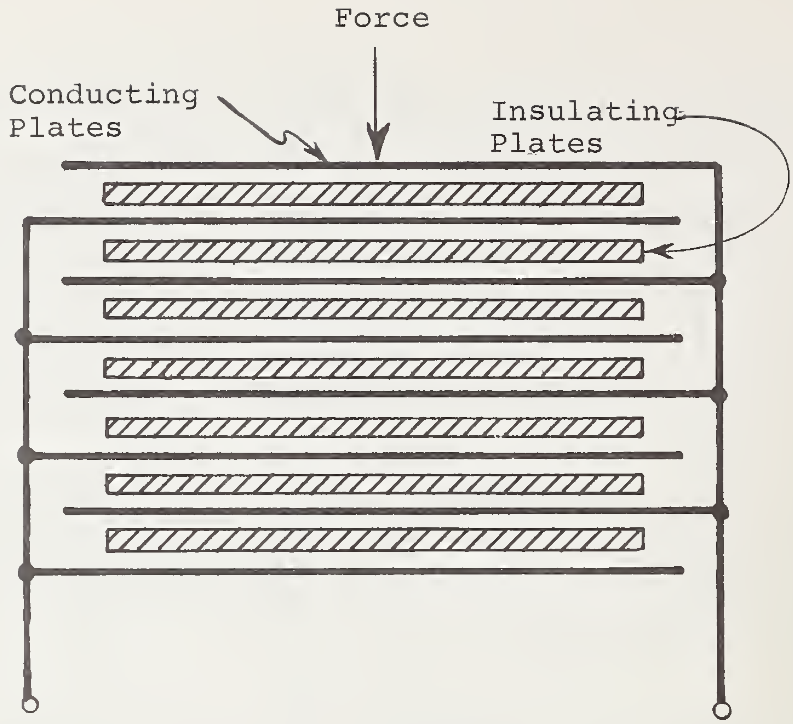


Figure 19. Layered capacitor.

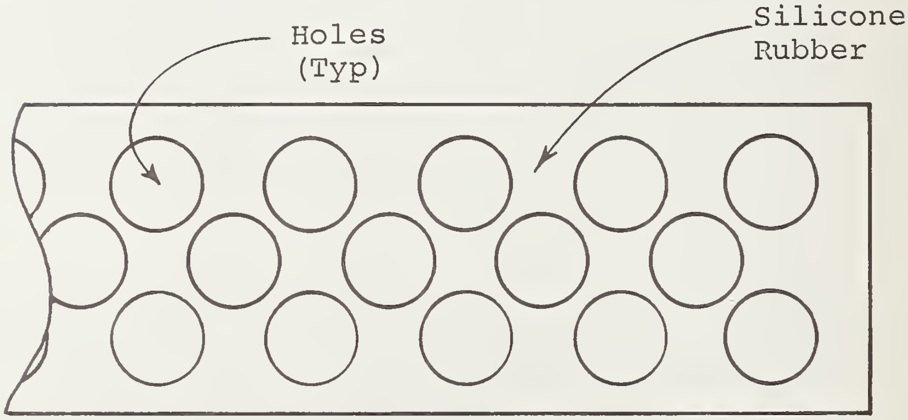


Figure 20. Silicone rubber insulator.

3. Upon compression, the holes prevent creeping or bunching of the rubber

4. There is less mass to produce a rebound found in many transducers when released.

When installed in the sensor housing or package, the bottom edge of the capacitor is retained on a fixed and solid base. In the case of the surface-mounted unit, this base is the bridge deck itself; with the universal type, there is a rigid base plate on the bottom.

When a truck tire or other compressive force is applied to the top surface of the sensor, the rubber insulators are compressed, thereby reducing the spacing between the capacitor plates and increasing the capacity of the sensor. The compression of a part of the sensor may be shown in a series of capacitors connected in parallel, with one of the capacitors increasing its value.

The capacity of a series of flat plates is given by:

$$C_{\mu\mu fd} = .088K \frac{A}{D} ,$$

where

A = Area of active dielectric (cm^2)

D = Spacing between plates (cm)

K = Dielectric content = 1.0.

If we assume a pad length of 1 m (100 cm) and a width of 2 inches (5. cm) for an area of 500 cm^2 for each of the plates and if the dielectric is set at 10 mils or .5 mm (.05 cm), the capacity is then:

$$C_{\mu\mu fd} = .088 \times 1.0 \frac{500}{.05}$$

$$= .088 \times 10^4$$

$$= 88 \text{ } \mu\mu fd/\text{plate}.$$

If we assume a total of 10 plates, the total capacitance is 10 x $C_{\mu\mu fd}$ = 8,800 μμfd.

At a maximum weight, we can assume that about one-third of the total length is reduced in dielectric spacing by one-half. The total pad can be represented by a series of three capacitors, each with a value of about 2,900 μμfd. When in use, two of the capacitors remain constant, and one of the capacitors becomes variable. If the spacing of the capacitor is reduced by a factor of Z (1/2), then the capacity will double. The total of the three sections will be 11,600 μμfd.

If the excitation frequency of the oscillator (see Figure 21) is set at 100 KHz and has an output voltage of 10 with a series registor of 180 ohms, then, from the reactance formula:

$$X_C = \frac{1}{2\pi fC} ,$$

the unloaded reactance is 180 ohms.

In the fully loaded condition, with a capacitance of 11,600 μμfd, the reactance becomes 137 ohms.

The following conditions represent the voltage across the voltage divider:

Normal: 180:180 = 5
Lowered: 180:137 = 4.3.

Capacity Pad Electronics - There are several techniques available for detecting the capacitance change in the sensor. Some of them are:

1. An RM oscillator circuit is used, in which the capacitor is part of the timing circuit of the oscillator.

2. The capacitor is placed in a bridge circuit and the compression represents a change or inbalance of the bridge. The bridge requires the detector or the signal source to have balanced inputs.

3. The capacitor is used in conjunction with a transmission line or network to present phase changes, which are easily detected.

4. The capacitor is used in a simple voltage divider circuit in conjunction with another reactance or resistance.

The proposed schematic is shown in Figure 21. The capacitor is used in a simple voltage divider circuit which is placed

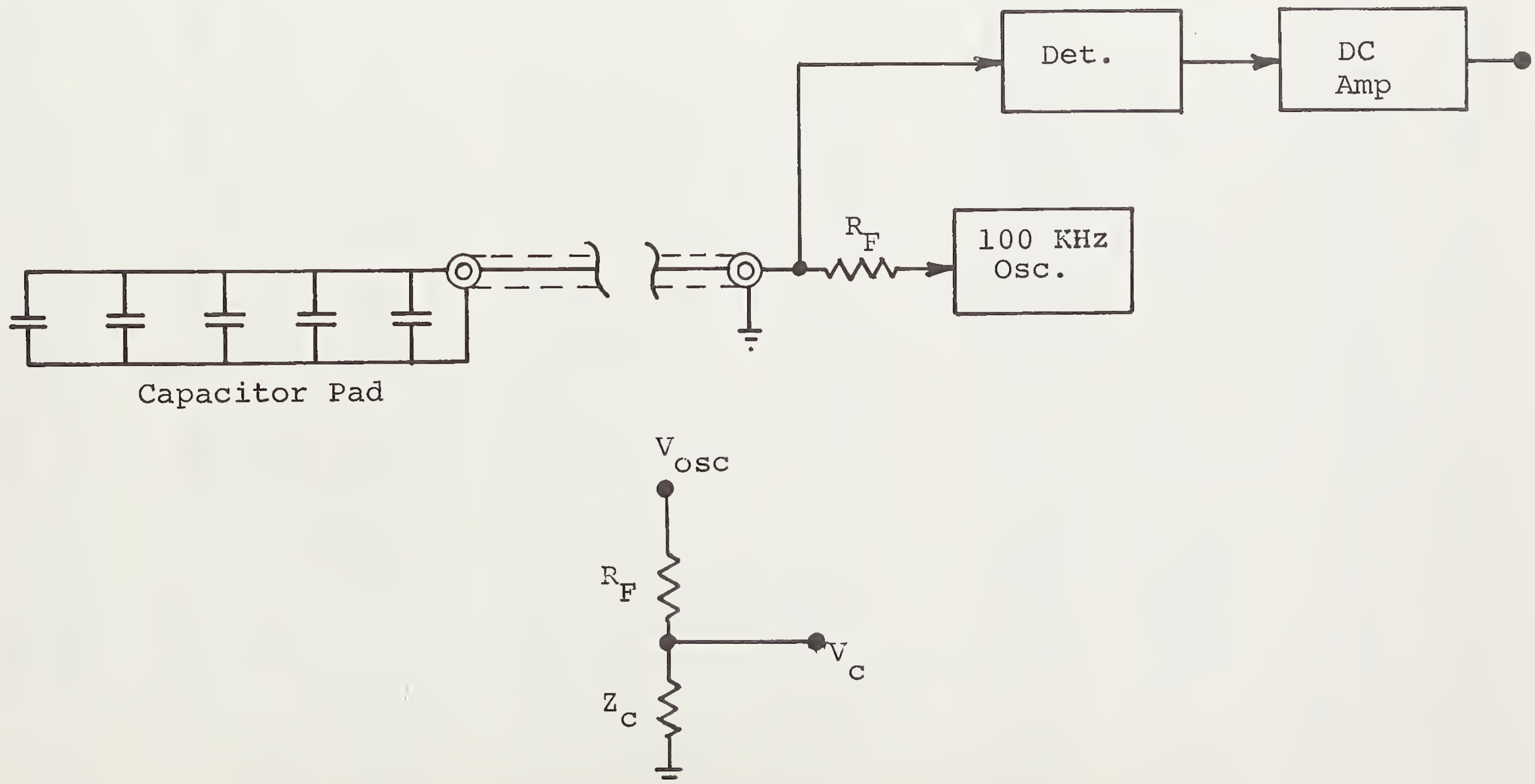


Figure 21. Capacity pad electronics.

across the output of a 100-KHz oscillator. At the center top of the voltage divider, the voltage is sampled and fed to a diode detector which produces a DC voltage from the 100-KHz signal. The voltage generator will normally be at a given level of about 5 when the pad is unloaded. When loaded, the pad's capacity will increase and the voltage will decrease (Figure 22).

The changing DC voltage is then applied to an operational amplifier which removes the DC offset and inverts the signal as well as amplifying the maximum output up to about a 20-v peak.

<u>Axle Count Processor</u>

The block diagram for the axle count processor is shown in Figure 23. The detected output pulse has the number one weight sensor and is used as the axle counter. The pulse (waveform) sequence for the axle counter is shown in Figure 24 and gives the timing for the logic.

As stated, the analog pulse (unprocessed) is received in the module; the pulse will vary in amplitude with truck weight. The pulse is passed throughout a threshold detector (Schmidt trigger circuit), where it is squared up. The shaped pulse is then applied to a one-shot multivibrator, which gives each of the axle pulses a standard width.

The axle pulses are then fed into a decoder counter and allowed to accumulate as long as the vehicle is present in the array. The presence pulse is used to gate the input of the counter so that no extra noise pulses are counted. As

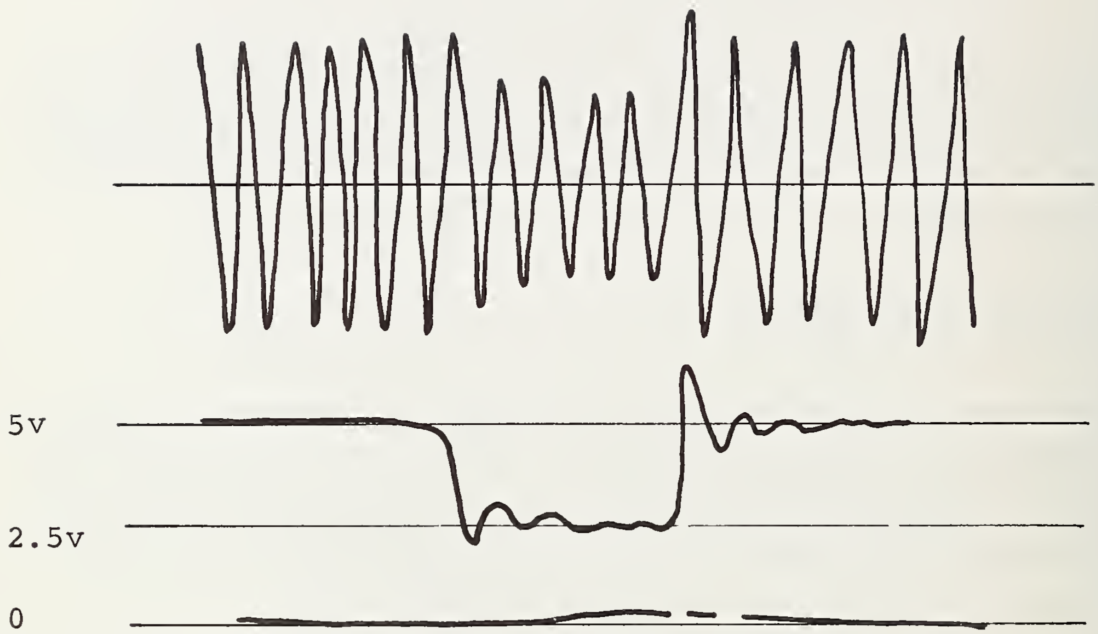


Figure 22. Oscillator excitation frequency.

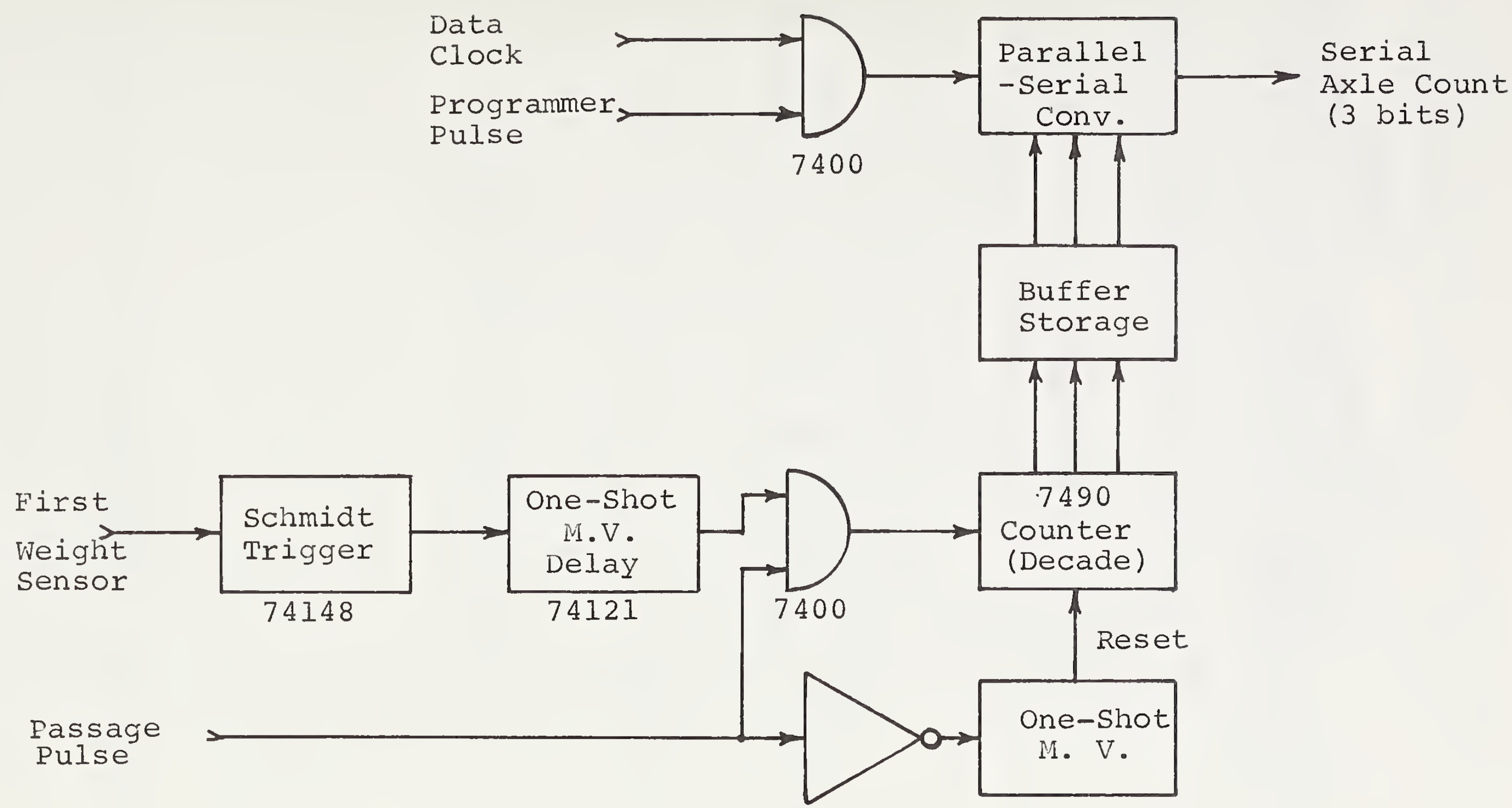


Figure 23. Axle count processor.

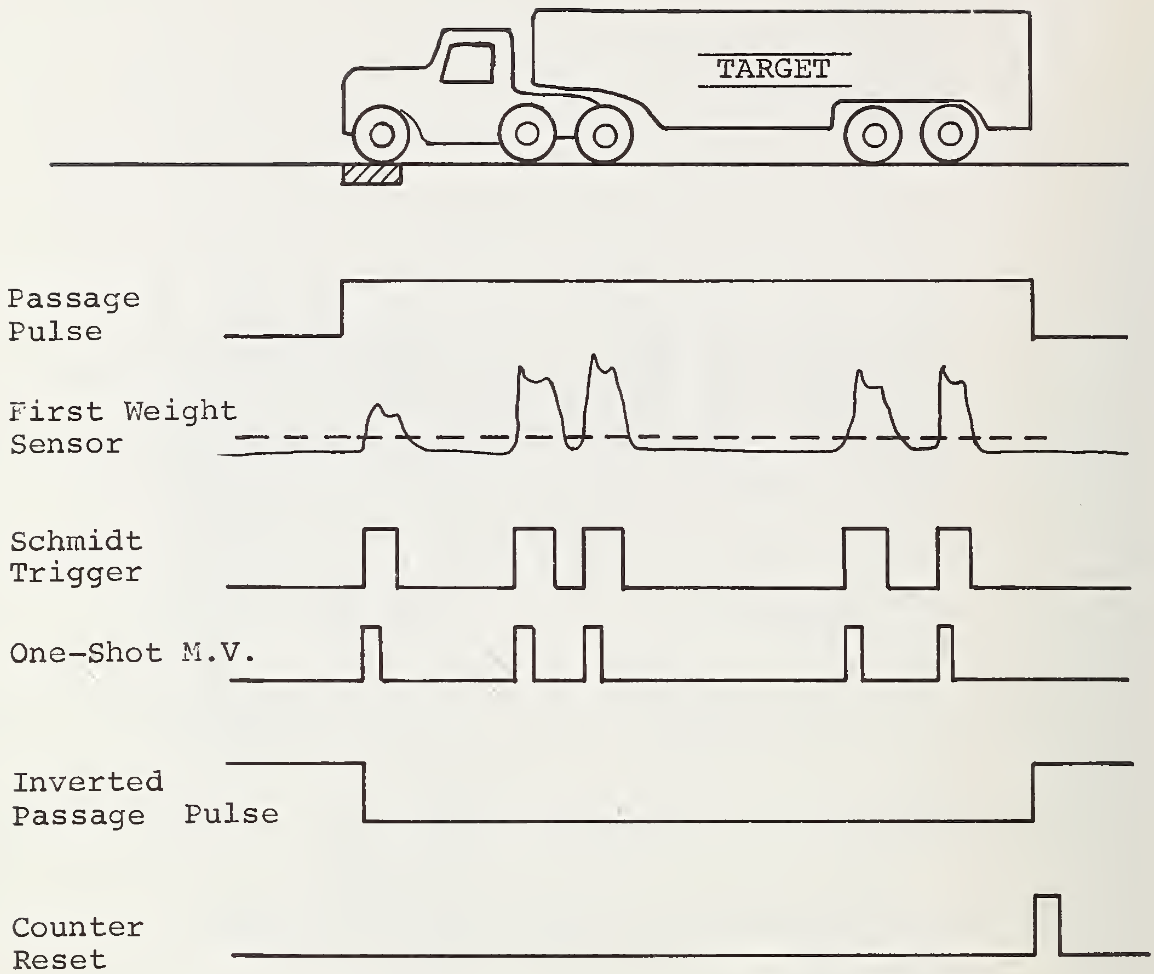


Figure 24. Pulse sequence for axle count.

shown, a "counter reset pulse" is generated from the trailing edge of the "presence" pulse which resets the counter.

The output of the 7490 decade counter is fed in parallel to a buffer storage and then into a parallel-to-serial counter. The output of the convertor is the serial format of 3 bits of information. Normally, the greatest number of axles that will be seen is five (3S2).

PROPOSED PASSAGE AND VELOCITY DETECTOR (PVD)

A dual-function module is proposed for the passage detector and the velocity detector, using Doppler radar. Doppler radar has been used for several years as a law enforcement tool, with little use made of the device for instrumentation. One of the reasons is that most of the radars utilized have an analog output in the form of a meter reading, which must be read by an operator. A few have strip-chart recorders. Most of the early radars were operated in "S" Band (2000 MHz) or "x" Band (10,000 MHz). Without going into the theory of operation, the practical limitation of the radar is discrimination of target, with the factor proportional to antenna size, and antenna size proportional to frequency (higher frequency, inversely smaller antenna size). Basically, the ability to discriminate between targets is related to the antenna beam width. The operating frequency of the proposed radar is 22,000 MHz (22 GHz).

The reason for the selection of Doppler radar and the operating frequency is cost. Currently, radar components designed specifically for traffic use are in low-cost production with a basic radar module costing about $150 in small quantities.

The dual-function module consists of two sections, the RF section and the processor.

The proposed radar is basically the same as others used in traffic work, with two exceptions:

1. The unit has a BCD-coded output for ADP

2. The unit is mounted under the deck and reads the the velocity through the deck.

RF Section

The RF section of the radar, as shown in Figure 25, consists of three basic parts:

1. Antenna

2. Transceiver

3. IF.

The antenna is a simple boom antenna measuring about 8 inches (20.32cm) in length. The transmitter and receiver energy utilizes the common antenna, with the antenna connected to the transceiver module via a short run of WR. 28 wave guide.

As stated earlier, the antenna looks through the bridge deck and is mounted only a few inches under the deck. The attenuation of the concrete deck [6-to-8 inches (15.24 to 20.32 cm) thick] is about the same as 200 ft (60.96 m) of free space, which is common in a Doppler setup. The actual

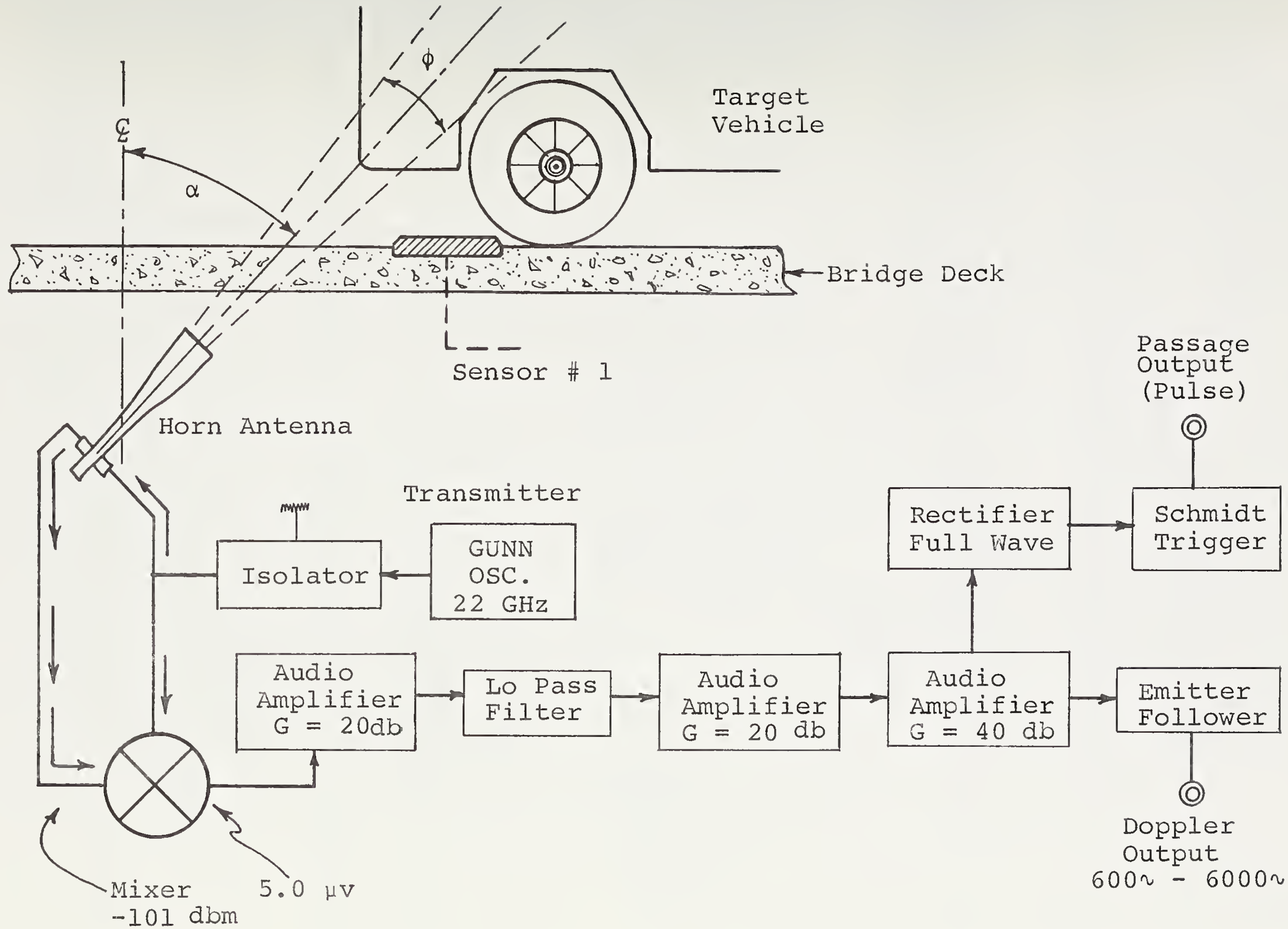


Figure 25. Doppler radar - RF portion.

range above the concrete to the target is only 3 to 5 ft (.91 to 1.52 m). The position of the antenna is such that the beam covers a target just as it passes over the number one load sensor and enters the array.

The antenna is a standard off-the-shelf, cast-alloy type, with a gain of 15 to 18 db.

The transceiver or receiver and transmitter portion of the radar is an off-the-shelf unit, such as that manufactured by Microwave Associates, in a variety of output power levels, as shown below:

Model	Po (MW)	Pin (DC)	Receiver Sensitivity
MA-86305	10	+5 v @ .3 A	-101 dbm
MA-86315	25	+5 v @ .6 A	-101 dbm
MA-86325	50	+5 v @1.0 A	-101 dbm
MA-86335	100	+5 v @1.25 A	-101 dbm

Each of the transceivers consists of a solid-state ferrite circulator (Gunn oscillator) and a solid-state diode mixer in a compact package [1.35 inches x 1.30 inches x .88 inch (3.43 x 3.30 x 2.24 cm)].

The doppler output, in the 600- to 6000-cycle range, is 5 μv.

Basically, the transceiver operates in the following manner. A CW signal (fixed frequency) is generated by the Gunn oscillator and emitted through the antenna to the target. The signal is reflected by the target; the reflected signal contains the original signal plus a signal containing the sum or difference of an audio signal (Doppler), which is a function of the target velocity.

The reflected signal (a small portion) is passed back through the antenna and into the mixer. In the mixer, a small portion of the transmitted signal is mixed with the receiver signal, producing the sum and difference frequency. The difference frequency is the Doppler rate frequency. In all of the Microwave Associates modules, the Doppler output level is 6 μv.

The output from the mixer is filtered and amplified to a level of 3 to 4 v. This output is buffered and applied as the analog Doppler output.

The passage pulse is generated by rectifying the Doppler signal which is applied to a Schmidt trigger circuit. The Schmidt trigger is a threshold circuit which will generate a square pulse, the length of which is the time the target remains in the antenna capture area (beam width). Representative wave forms are shown in Figure 26. Relative timing after derived control pulses are also shown.

Processor

The velocity or speed of the target is presented to the ADP equipment in a digital format giving the count of the Doppler frequency, not velocity, in mph. The reason for this is that the conversion can be done in the central processing equipment and not be repeated in each of the lane packages.

The block diagram of the Doppler is shown in Figure 27. The sine wave output from the RF section is squared up in a Schmidt trigger. The pulse string is applied to a one-shot multivibrator which gives a standard width pulse.

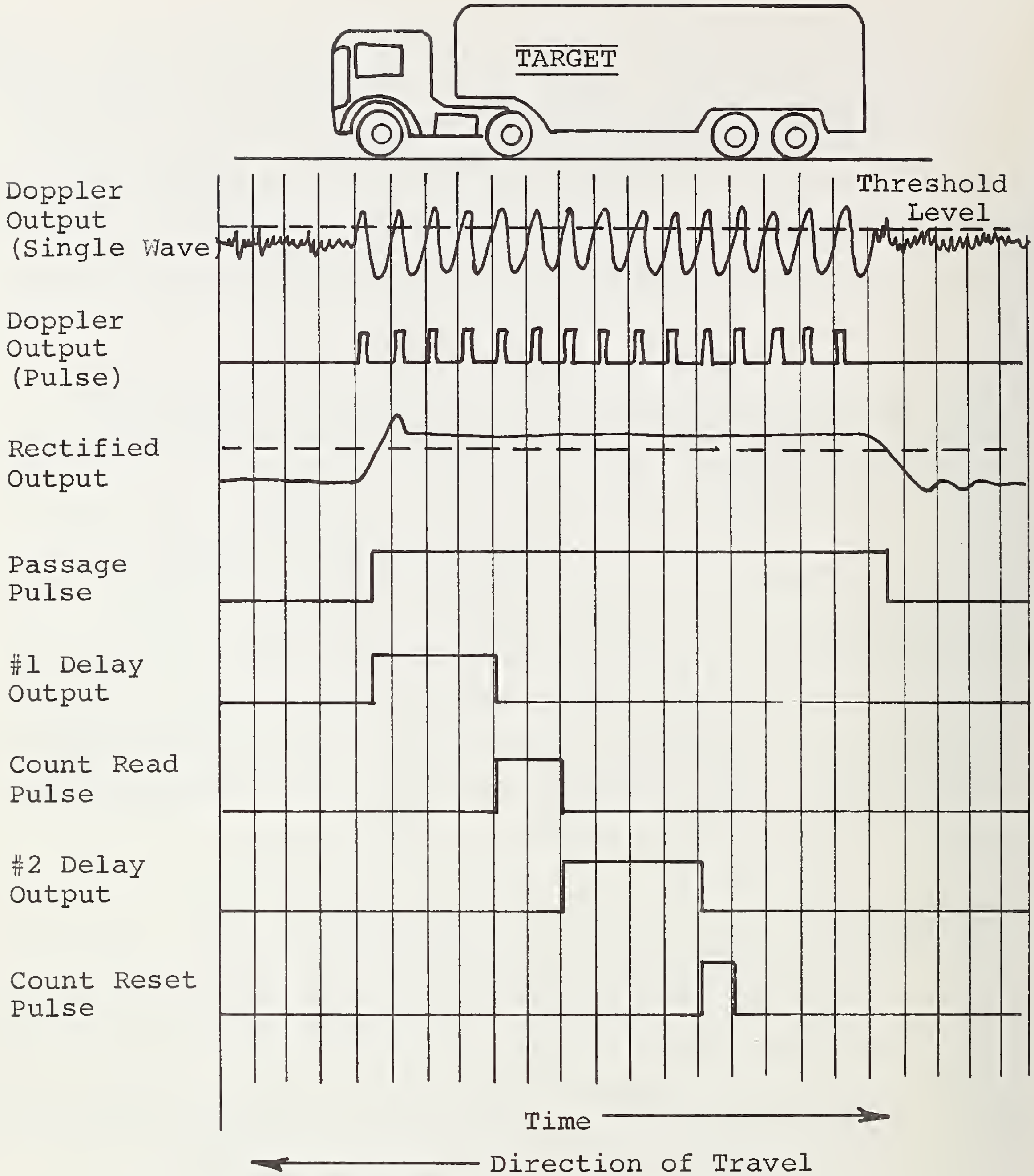


Figure 26. Doppler/passage pulse timing.

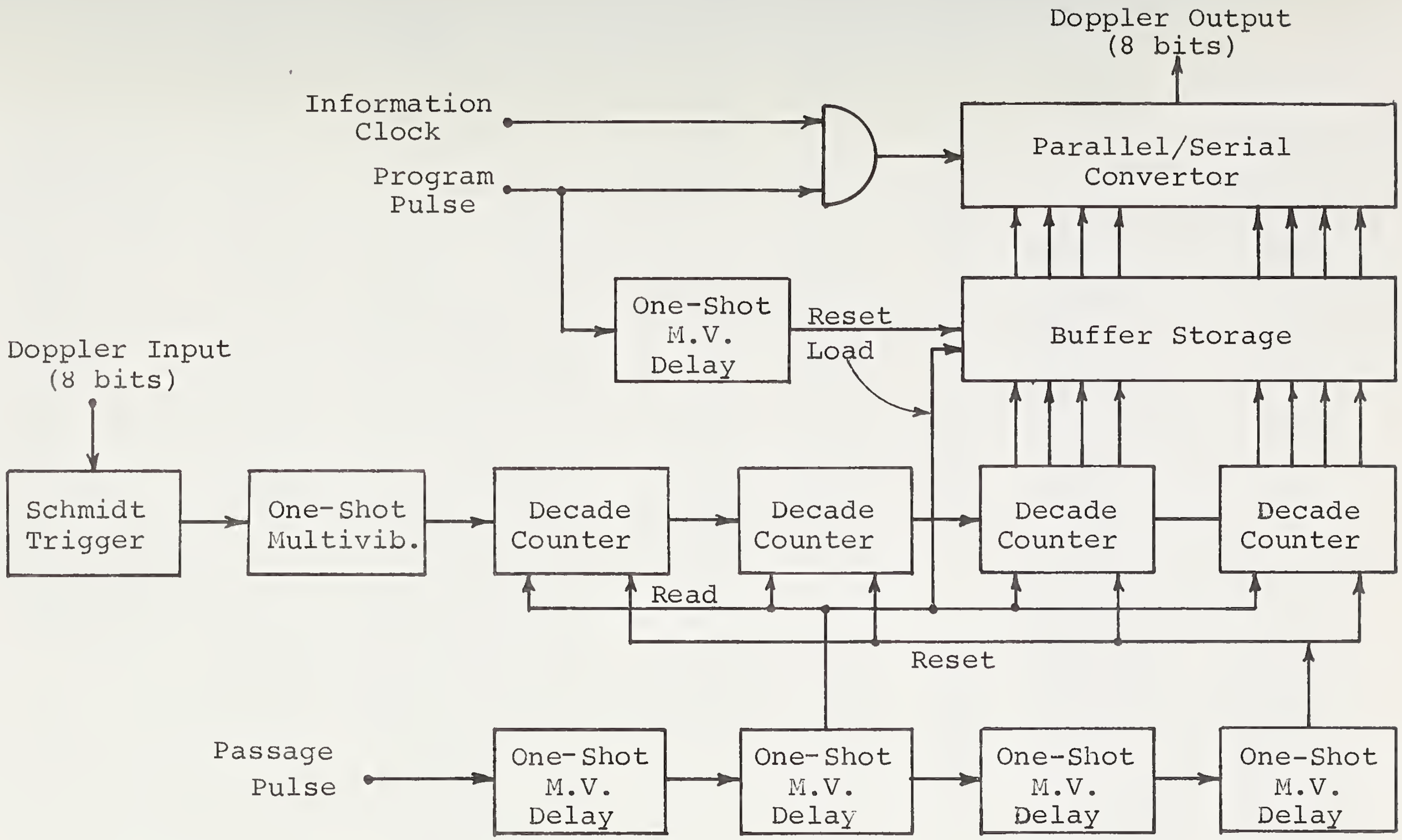


Figure 27. Doppler processor.

The pulse string at the Doppler rate is applied to a series of counters which consist of four decode counters. The last two decoders are read out into the output format circuitry.

In order to hold the bit rate and information rate to a minimum, only the most significant figures of the Doppler frequency are read out in the following manner:

Doppler frequency	600 cps	6,000 cps
Count	6	60

As shown, the count could be made in six bits (64), but two of the bits are used as buffers.

The read (count) pulse and the counter reset pulse are derived from the leading edge of the passage-sensing pulse.

The count pulse is delayed from the leading edge of the passage-sensing pulse long enough for the frequency to settle down (near the middle of the target). The count pulse is long enough to read the lowest frequency into the counter. At the same time that the count is read, the count is transferred to the buffer storage. The count is locked into storage when the read pulse is removed. At the same time (read time), the count data is read into the parallel/serial counter from the storage. The data stays in storage until after the programmer reads the count data out in serial form to the multiplexer. The serial data is read out when the clock is applied through the clock gate. This function is also derived from the passage-sensing pulse.

Mechanical Construction

The lanal module for the PVD can be packaged in the form of two small modules. The first, the antenna and RF section, is mounted directly to the bridge deck. This package should weigh about 1.5 lb (.68 kg) and measure about 8 inches x 3 inches x 4 inches (20.32 x 7.62 x 7.16 cm). The logic will be contained in the main lane package which is mounted on the lower lip of a girder.

LANAL PROCESSING PACKAGE

The block diagram of the "Lanal Processing Package" (LPP) is shown in Figure 28.

The LPP has two fundamental sensor packages:

1. The PVD

2. The weight sensor.

All of the other information needed is derived from these sensors, on the bridge, in this package in the bridge processor or at the data reduction site (ADP).

The data from each of the sensors is in serial form with the following number of bits used for transmission:

1.	Velocity	8 bits
2.	Number of axles	3 bits
3.	Weight (6 sensors)	24 bits
4.	Passage	N/A.

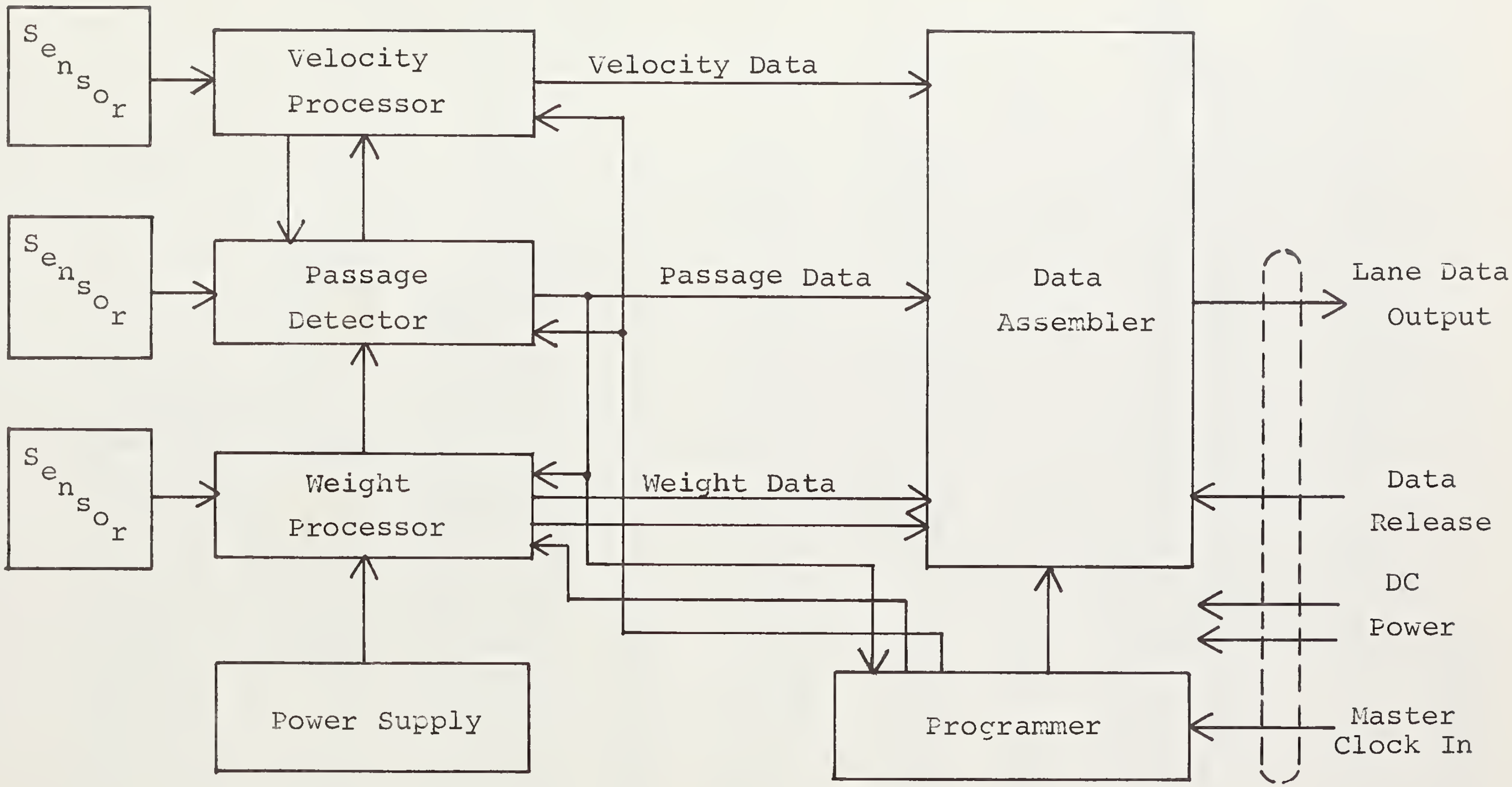


Figure 28. Lane passage block diagram.

The passage-sensing pulses (beginning and end of passage) are sent down the transmission line in front of the data format with enough time delay so that the timing signals may be inserted on the tape at the processor.

Excluding the passage-sensing pulses, a total of 35 bits are required for the full identification.

The data transmission rates, both out of the LPP and the Bridge Processor Package (BPP) is set at 2,400 bits per second.

If a truck message length of 100 bits were assigned, there would be a capacity for the transmission medium of 24 trucks per second.

The reason for choosing the 2,400-bps rate is both for recording of the data and the possibility of relaying the bridge data in real-time bases to a central processor by use of voice-quality telephone lines and a data phone. As the lane package is currently designed, each of the LPP's is compatible with phone lines for data transmission.

There are basically three data blocks to assemble into the message coming from the bridge. The block diagram of the programmer is shown in Figure 29. The data process begins with the leading edge of the passage pulse and ends with the trailing edge.

The programmer flip flop starts counting clock pulses upon the arrival of the passage pulse (BOP). The flip flops are opened and start to count the 24,000-cps clock ratio.

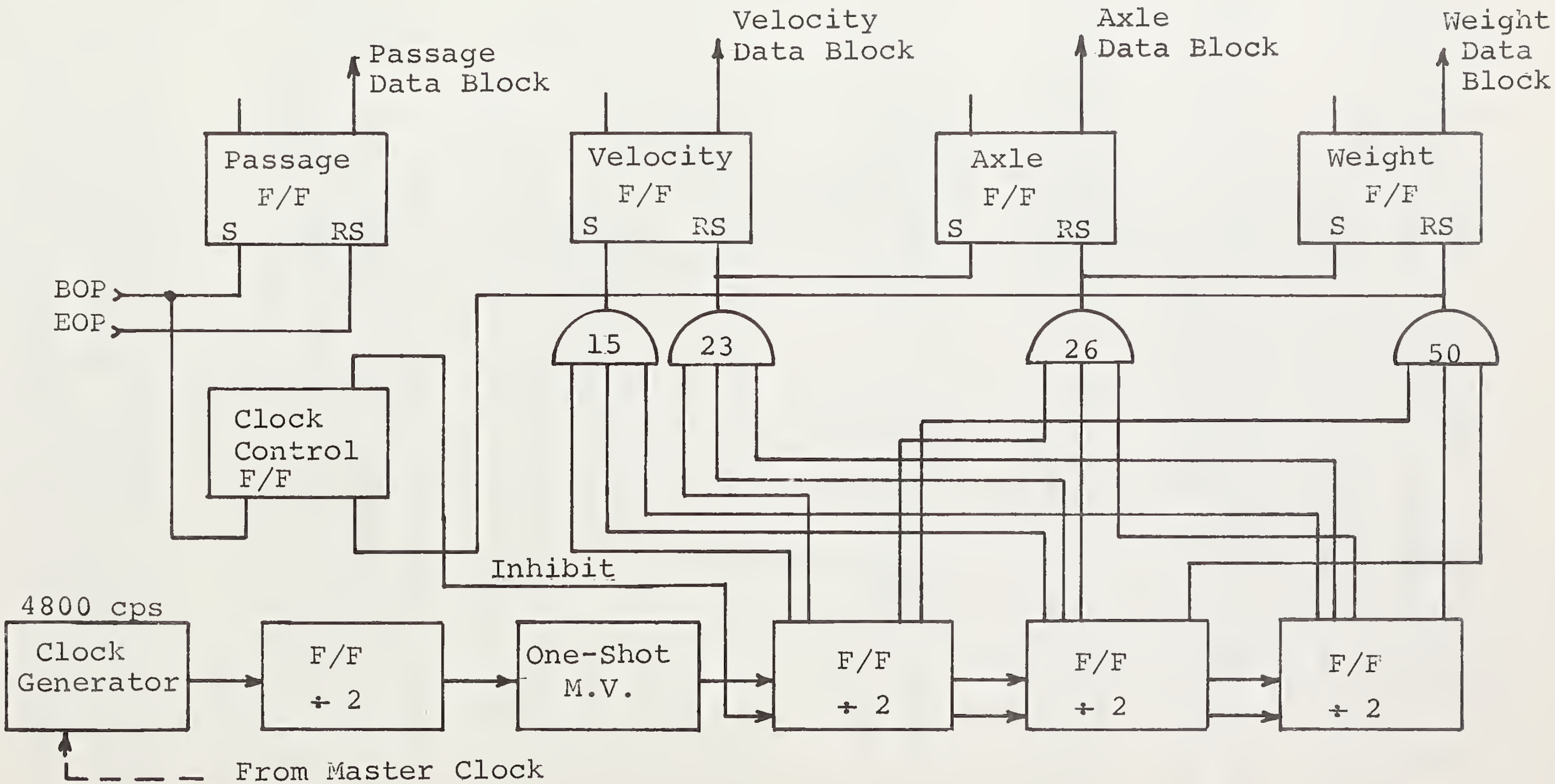


Figure 29. Lane programmer.

Count detectors, gated outputs from the counters, determine when the data is inserted into the format. The velocity data starts at the 15th count, and ends on the 23rd count. The axle data begins on 24 and ends on 26, and the weight occupies from 27 to 50 (see Figure 30). The times between pulses are stored by format control flip flops which, in turn, hold on the data gates in the assembler.

The last pulse out of the assembly is the EOP which can come at any time, depending on velocity and length of truck.

WEIGHT SENSOR PROCESSOR

The output of the weight sensor electronics is an analog voltage pulse, with a maximum value (peak) of about 10 v which represents an axle weight of about 14,000 lb (6,350 kg). (Actually, this is one side of the axle and represents the wheel or dual wheel weight.) The voltage pulse is applied to a processor which converts the pulse voltage value to a 4-bit binary code.

The 4-bit code gives 16 values of weight, if we use 14 codes for 1,000 lb (45.4 kg) per step. If necessary, the extra 2 bits can be used to describe the weight under 1,000 lb (45.4 kg).

Rather than use linear processing of the weight pulse, no thought has been given to stripping the output pulse by using a log amplifier or other exponential shaping. When digitizing, this gives more bits (steps) in the lower weight range and keeps the percentage error low at the lower weight ranges.

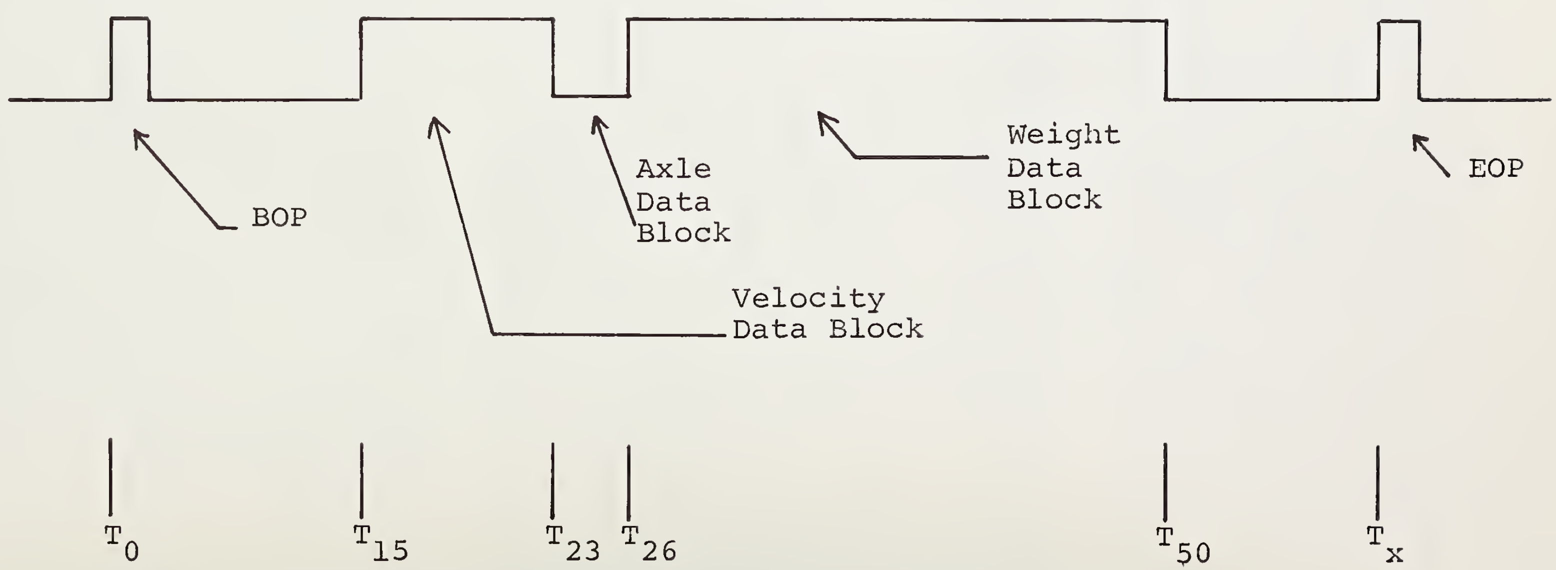


Figure 30. Data format.

The weight pulse is applied to an analog-to-digital convertor (ADC) (Figure 31) similar to those used in digital volt meters. These devices must be sampled or strobed at the point in time that the measurement is to be made. Ideally, the sample should be taken near the middle or rear edge of the pulse after the reset time "ringing" has been reduced. The new solid-state convertors can sample in less than 10 milliseconds, which is much less than the passage time across a sensor at 80 mph (128.7 km/hr).

In addition to the digitizing of the pulse, the sensor output pulse also is shaped (Schmidt trigger circuit), as shown in Figure 31, in order to derive timing information from the pulse.

The square sensor pulse is delayed by a 74121 one-shot and applied to a second 74121 as a pulse generator. As shown in Figure 32, the pulse timing is adjusted to fall in the middle of the sensor pulse, thereby insuring the ADC a portion of the settled pulse.

The output of the ADC is available for a short period of time during and just after the sample pulse. Therefore, in order to reprocess the four lines, the information must be stored. Storage, in this buffer storage, is in the form of four flip flops or shift registers. The information is set into storage by a read pulse, the simple pulse from the ADC.

If there were only one sensor or one target to deal with, the processor could be used at this point. Unfortunately, this is not the case. Six sensors in an array are being

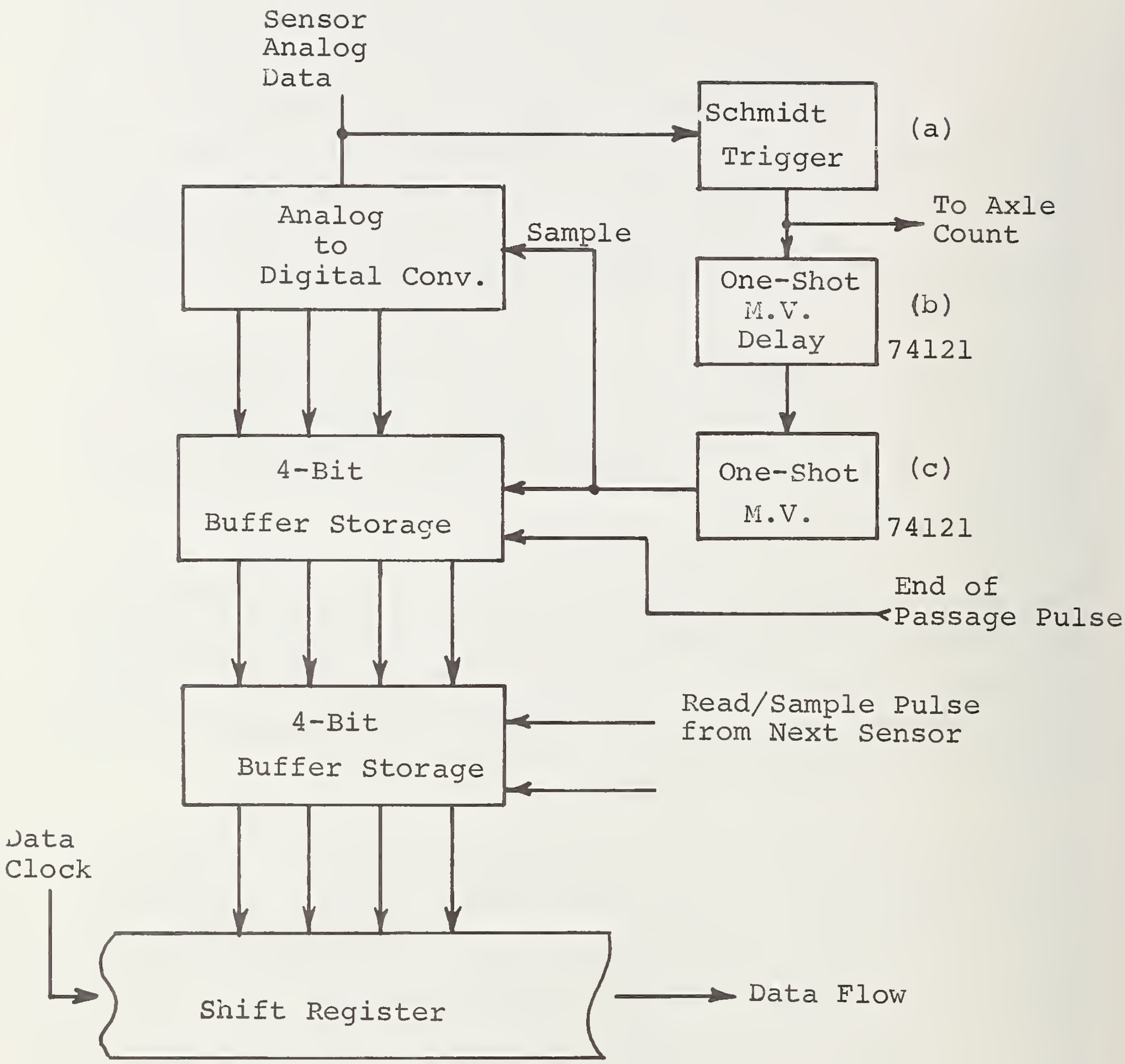


Figure 31. Weight sensing processor block diagram.

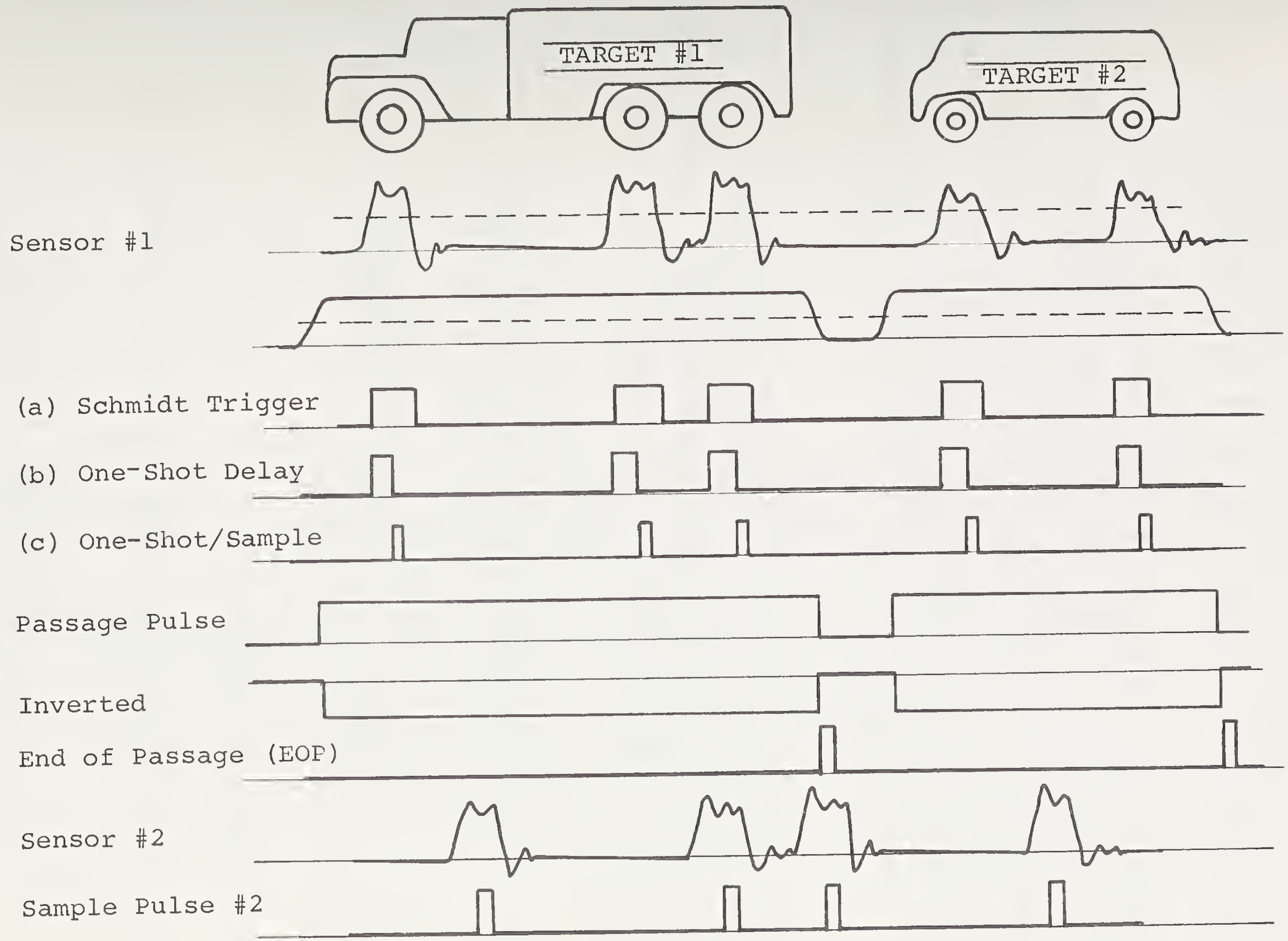


Figure 32. Pulse timing for weight sensor.

used and there is a possibility of a truck entering the array before a preceding truck has left the array.

The PVD's look at only those targets directly above the number one sensor, and, therefore, the output from the remaining sensors is sometimes after the end of the passage pulse. A new passage pulse will be generated before the first truck is out of the array. In the format for transmitting the data, all of the sensors' information (for one vehicle) must be in storage before being recorded out in serial form.

In an effort to save the first target information, the information in the buffer storage is transferred into a second buffer (flip flop) when the next sensor in the array generates a read/sample pulse (the middle of the sensor pulse).

The first buffer storage is reset by a pulse generated by the trailing edge of the passage pulse (Figure 32).

The second buffer is reset by a pulse generated by the last sensor in the array. This pulse is also used to operate (start) the entire output program.

BRIDGE PROCESSOR PACKAGE

The block diagram of the "Bridge Processor Package" (BPP) is shown in Figure 33.

The BPP will process three channels (lanes) of information and store the three channels plus a time channel.

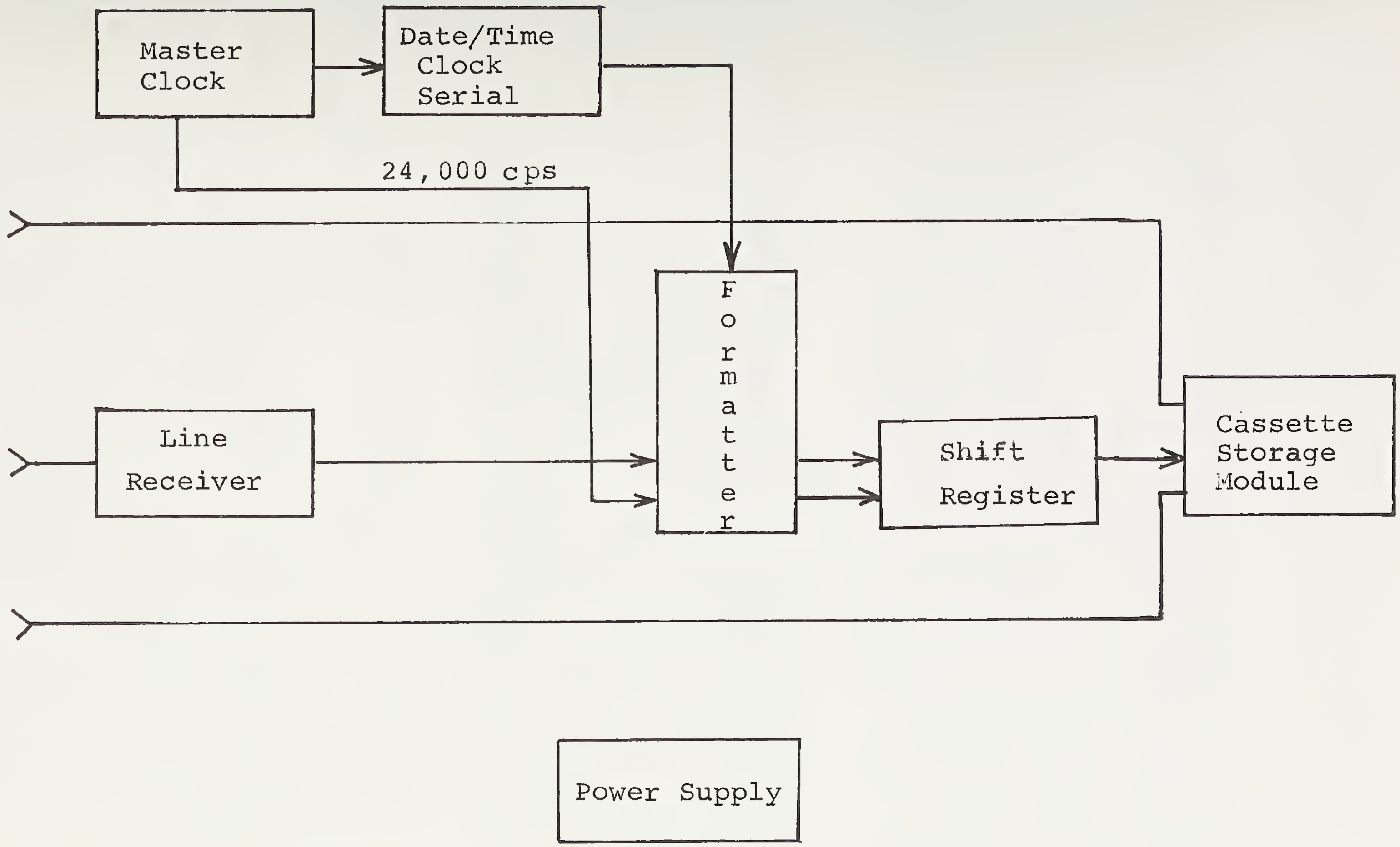


Figure 33. Bridge processor package (BBP).

As shown earlier in Figure 30, the two timing pulses are on both sides of the darker blocks and must be stripped out before being stored. The passage pulse (BOP) is detected and holds the data block from the bridge until 12 bits of data time information is recorded into the central shift register storage.

The data blocks are then gated into the shift register until the 50th clock pulse (end of data) is detected. At this point, time again is inserted into the register in the form of seconds (4 bits) and tenths of seconds (3 bits) in the last seven slots of the register.

When the storage register is full, the information is clocked, at 24,000 cps, into the cassette storage module which is started on arrival of the passage pulse.

The cassette has 1.5-million-bits capacity or a capacity of .5 million bits per lane of traffic (3 lanes). If an average target occupies 100 bits (including start-up), the capacity of the cassette is 5,000 trucks in any lane.

Typical truck loading of an interstate highway can be considered as about 1,500 trucks per day or about 1,300 trucks in the truck lane per day (11). The cassette will give about 2 to 4 days of operation for the truck lane, and many more days of operation for other lanes.

DATA REDUCTION AND INTERPRETATION

Since the recommended "in-motion" weighing system is the direct-sensing form, due to the unresolved question on the practicality of using seismic sensors, and since the recommended approach is to use a universal-type acquisition and recording system which is effectively transducer-independent, the data reduction necessary becomes straightforward; i.e., the recorded data will always be in the same format with the same content and data definition. The data will also always be in a digital form.

Although the evaluation results of this study effectively disqualified the use of a seismic sensing system without an adequate evaluation program, a discussion of the data reduction process necessary to the reduction of seismic data is presented in Appendix D. The discussion is based on the knowledge of these investigators at the time this report was prepared of the content and characteristics of bridge dynamic truck load data contained in the seismic signal.

REQUIREMENTS

To minimize the initial investment necessary to achieve an "in-motion" weighing system for bridges, the on-site processing should be held to the minimum necessary. The extent of the on-site processing should be limited to determining if all measured dynamic axle loads are less than the 2,000-lb (097-kg) threshold. If they are, the data is discarded. This minimizes the storage hardware necessary

on-site. All other processing functions should be performed off-site on a general-purpose computer which already exists within the inventory of FHWA to further minimize costs. This tends to maximize the reduction functions performed off-line. However, it also provides a great deal of flexibility in the on-site hardware configuration. A fairly simple bit-string format and a computer-readable medium forms the essential interface.

The functions which the reduction part of the system must perform are as follows:

1. It must read, from the storage media or other source provided by the acquisition part of the system, the raw data block for each measured vehicle and place it in an operating storage media.

2. Each variable contained in the data block must be extracted, scaled, unbiased, and converted to the proper units from the recorded bit string. The variables which should minimally exist and be derivable from the encoded data block are as follows:

   t_{ARR} = Arrival time

   j = Lane number

   V = Vehicle speed

   t_{AX_k} = Axle time for the k^{th} axle

   W_{DAX_k} = Total dynamic axle load for the k^{th} axle,

where

$$1 \leq k \leq K,$$

and

K = total number of axles (this would be a derived value).

The end of a vehicle's set of data will be followed by an end-of-record indicator placed there by the acquisition recording hardware, or set off in a distinct manner by format definition, etc.

3. For each axle, the reduction software must calculate:

$$W_{SAX_k} = f(W_{DAX_k}),$$

where

$f(x)$ is the conversion function from dynamic axle load to static axle weight,

and where

W_{DAX_k} is the dynamic axle load for the k^{th} axle,

and

W_{SAX_k} is the static weight for the k^{th} axle.

The determination of the static axle weight from the acquired dynamic axle load will be the most complex portion of the reduction process. All of the accuracy achieved in sampling the dynamic axle load can be lost unless care is exercised in establishing the definition of f(x). A great deal of good work has been performed in analyzing vehicular dynamic pavement load functions, as was discussed in the load sensor in-motion requirements. All of the properties of dynamic axle load functions must be considered in this portion of the data reduction process.

During this calculation, the number of axles, K, could be determined for vehicle by counting existing axle loads in the bit string. Also, during this calculation, each dynamic axle load can be tested to determine if any one of them exceeds a 10,000-lb (4,536-kg) threshold. If they do not, the logic must be set such that the total vehicle dynamic load and the dynamic axle loads are not output. Conversely, if any axle exceeds a 10,000-lb (4,536-kg) dynamic load threshold, the logic should be set such that the total vehicle dynamic load will be determined and output as a part of the reduced data.

4. If the total dynamic load is to be determined, then

$$W_d = \sum_{k=1}^{K} W_{DAX_k}$$

expresses the total vehicle dynamic load calculation which must be performed

and

$$W_s = \sum_{k=1}^{K} W_{SAX_k}$$

expresses the total vehicle static weight which must be determined.

If $W_s < 10{,}000$ lb (4,536 kg), the logic should be set such that W_s is not output. If $W_s \geq 10{,}000$ lb (4,536 kg), the logic should be set such that W_s will be output.

5. The distance between the axles of each vehicle must be determined, e.g.,

$$\Delta x_{k-1} = V(t_{AX_k} - t_{AX_{k-1}})$$

for $2 \leq k \leq K$,

where

- K is the number of axles for the current vehicle being reduced,
- V is the speed of the current vehicle,

and

- t_{AX_k} is the time at which the k^{th} axle was sensed.

6. A comparison of each vehicle's axle configuration against axle configuration tables, for example, representing each truck type, must be performed to determine the truck type for each vehicle.

7. The headway between trucks in each lane must be determined. It can be defined as the increment of time between the previous truck's arrival time and the arrival time of the truck currently being processed in the same lane.

   The headway is determined from:

   $$\Delta t_H = t - t_H ,$$

   where

   $t_H = 0$ for the first vehicle in the sample and subsequently becomes $t_H = t$ of the previous vehicle.

8. The above functions must then be repeated, in all lanes, until the last truck in the sample has been processed. This point should be recognizable by encountering an end condition in the data storage media furnished by the acquisition system.

During the course of reducing the raw truck data, or upon completion of the reduction process, the resulting reduced data must be output on hard copy and retained for future analytic purposes on computer-readable storage media. The output data should be organized and stored in a manner which allows efficient use of the reduced data for analytic purposes.

A requirement for the retention of the raw data for some reasonable period should be established. It should be at least retained until the reduced data has been analyzed for discrepancies, dropouts, etc.

DATA REDUCTION DESIGN CONSIDERATION

As in all data acquisition systems, this system can be anticipated to develop ambiguities in the recorded data. Some of these will be due to inconsistent lateral behavior of the vehicles on the deck. The recommended acquisition system will insert zeros in the bit string for that portion of the transit which occurs after a lane change. The only practical approach is to discard such samples. In order to handle lane changing and recover such a sample, a great deal of logic and possibly some predictive capability would be required in the data-reduction software. Such a capability is a luxury in a prototype system and does not warrant the investment necessary to implement it. Such a capability could be included subsequent to achieving a successful system.

A real difficulty arises when a sample or samples appear to contain valid data when in fact they do not. Such circumstances may arise from particular lane-changing events, from equipment malfunctions, etc. No real cure-all technique exists that will provide for discarding or recovering such samples. In order to develop techniques capable of sophisticated recovery of raw data, it is first necessary to acquire an exhaustive and detailed knowledge of the specific data collected and the forms of problems which arise in it. This implies the need to have data-reduction

computer programs that are capable of performing selective diagnostic operations on the raw data. Also, the main data-reduction software should be capable of selective restart and partial file reduction; i.e., it should not be necessary to reduce a complete file, deck, or tape in order to re-process only a small portion of the raw data file.

REDUCTION PROCESS

Since the reduction requirements only include the reduction of the data acquired from the universal acquisition and recording system for direct-contact-form transducers, the reduction process is, in general, straightforward, as indicated in Figure 34. However, three problem areas exist within the total process. These are:

1. Resolution and handling of load data ambiguities

2. Resolution and handling of classification ambiguities

3. Establishing the dynamic axle load function.

The problems of resolving and handling load data ambiguities and establishing the dynamic axle load function both occur within the function block "Establish Single Axle Dynamic Load Function $f_{AX_k}(t)$" in the flow diagram in Figure 34. The problem of resolving and handling classification ambiguities occurs in the classification subroutine, which is discussed later in this section. The resolution and handling of some of the load data ambiguities is

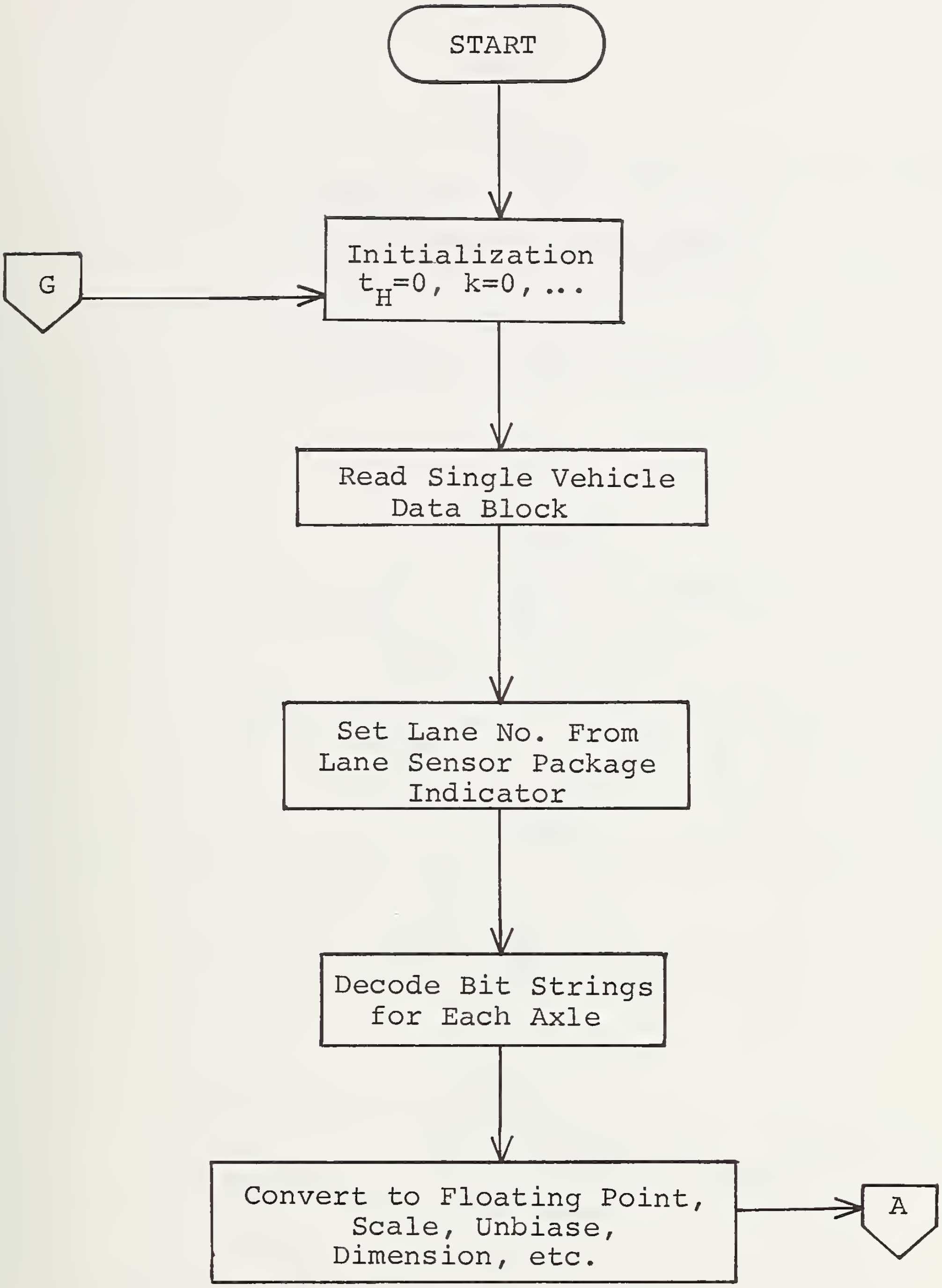


Figure 34. Data reduction process.

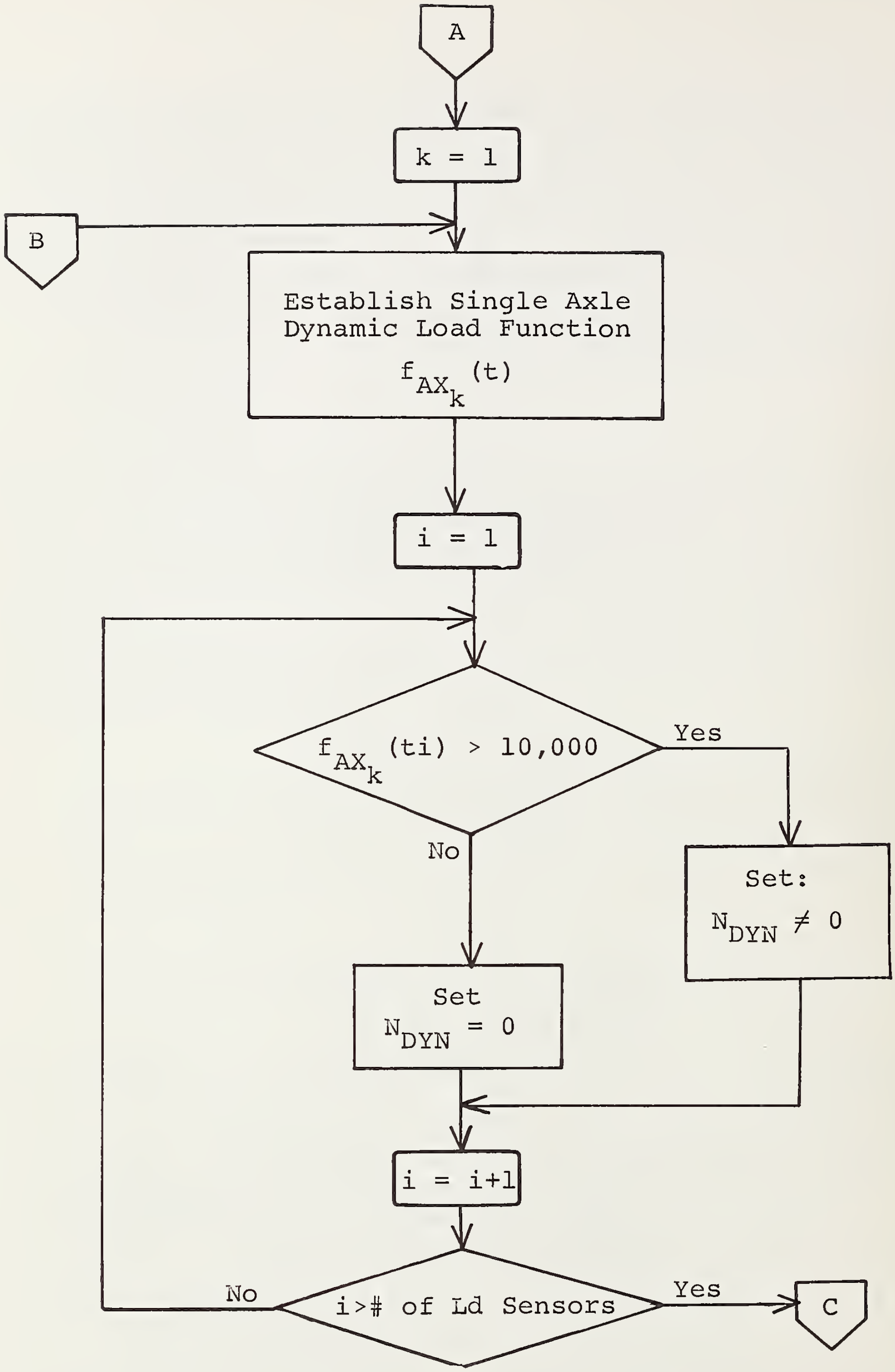


Figure 34. Data reduction process. (continued)

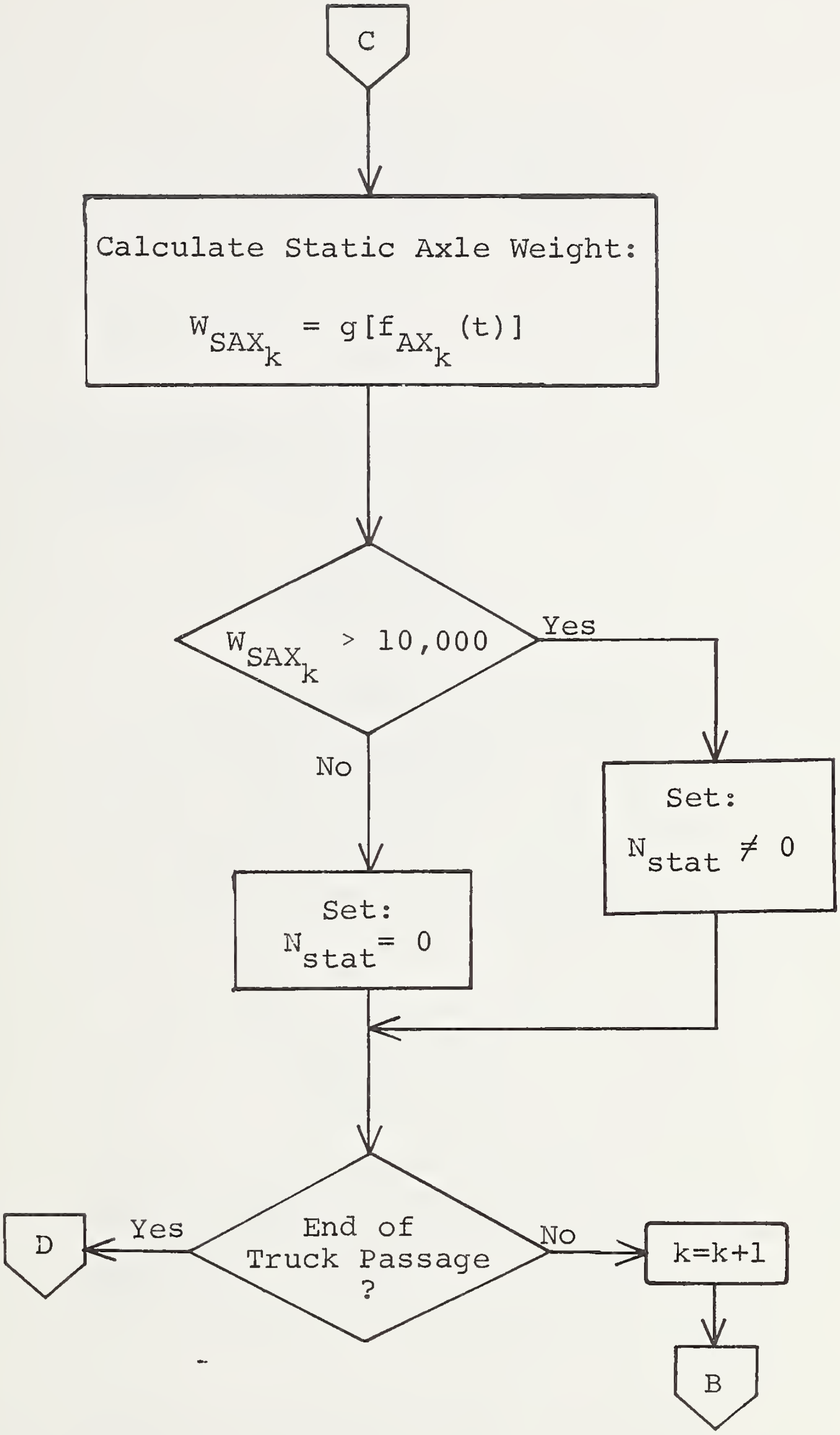


Figure 34. Data reduction process. (continued)

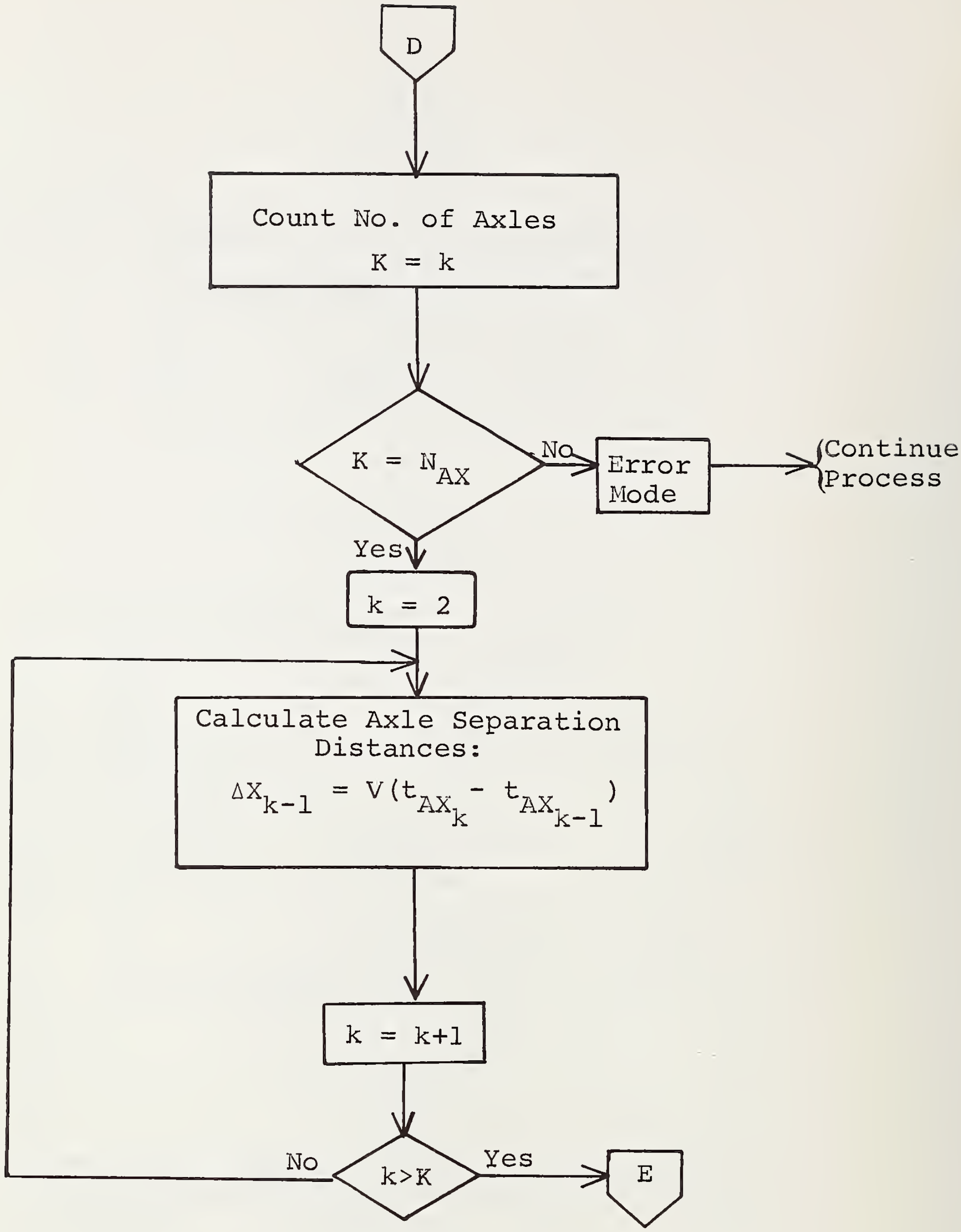


Figure 34. Data reduction process. (continued)

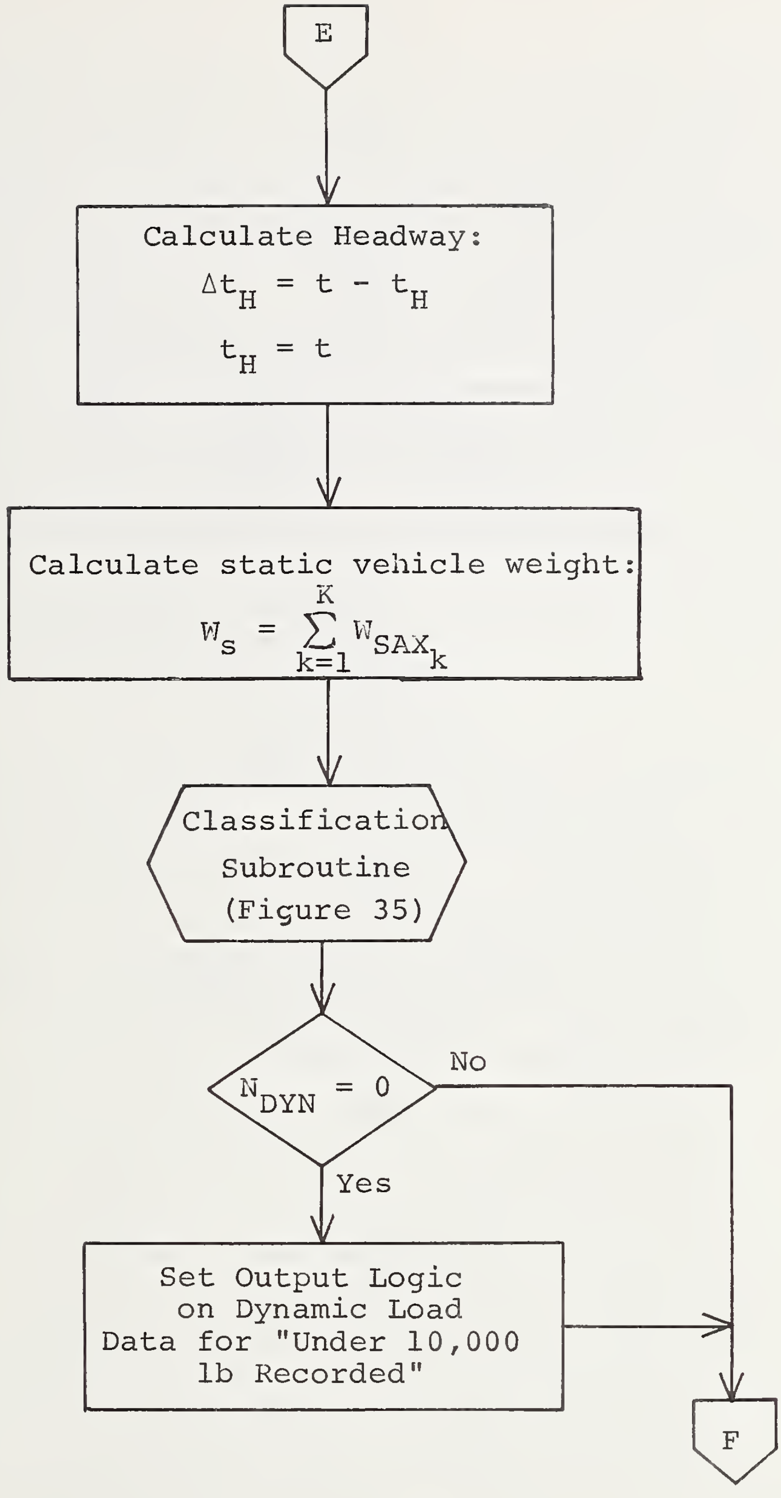


Figure 34. Data reduction process. (continued)

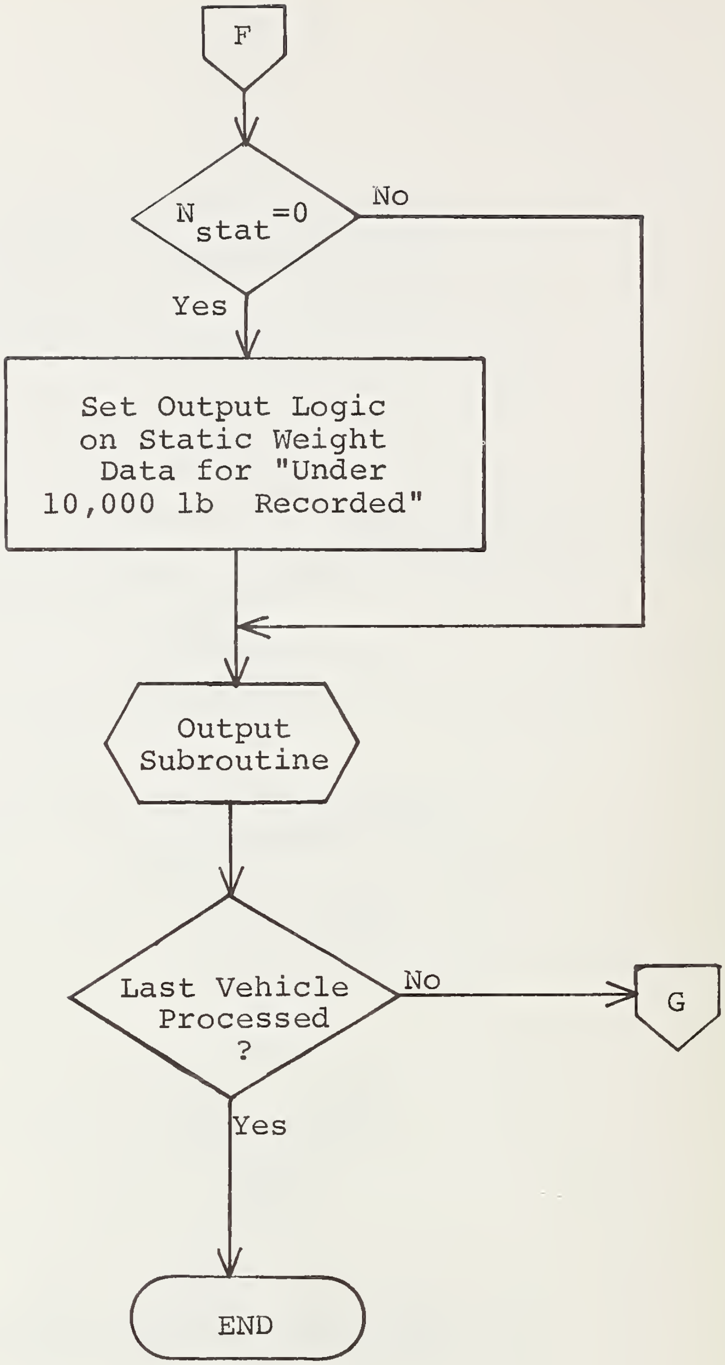


Figure 34. Data reduction process. (continued)

accomplishable by use of the automatic zeroing which will occur in a bit string for those load sensors missed by a truck's wheels. However, more comprehensive resolution can only be accomplished after the form of the ambiguities has been identified; e.g., if the passage-velocity detector does not provide an adequate signal return from trailer hitches and tongues, special logic must be incorporated in the data-reduction program to recover the total truck sample for proper processing. In general, this requires the gaining of experience in the characteristics of the acquisition and recording system. Until such experience is gained, an arbitrary discarding of the data, except for diagnostic purposes, should be made.

The problem that poses the largest initial analytic requirement is the establishment of the dynamic axle load function from the load sensor array. Since it is desirable to accurately determine the static weight of truck axles, it is interesting to note that, the more accurate the determination of the dynamic load function becomes, the more accurate the determination the static weight becomes. It is not clear to the investigators of this study why some of the numerous previous investigators did not realize this fact and exploit it. At the beginning of this project, it was felt by these investigators that a significant part of a truck's dynamic axle load function, which occurs as it transits a bridge, must be well defined; i.e., if the sample were sparse, an interpolative filling-in process should be used, and, if the sample were of short duration, an extrapolative process should be used to extend the function to a limit, on each end, which is dependent upon the individual sample. A review of the literature indicated that

primarily simple averaging or statistical processes have been used in prior work. However, one study performed by Herrick (6) essentially confirmed the views of these investigators. The method referred to as "VWEIGH" by Herrick has the characteristics of the process hypothesized by these investigators at the beginning of this study. Concerning this method, Herrick states, "...consists of interpolating between platforms by means of polynomial curves fitted through the data of each successive group of three platforms. The whole interpolated data record was averaged to yield a key value which in itself was better than the average over the platform only. The interpolated data record was tested to see where it crossed the key value. It was then averaged between the first and third crossings. This worked quite well. Although the method was not fully developed, it appears to yield excellent accuracy." The platforms referred to are weighing platforms which are equivalent to the load sensors in this system. The three-platform polynomial used by Herrick was obviously a quadratic. Sinusoidal fits should be evaluated against the use of polynomial fits.

In his discussion of this method, Herrick mentions the expense involved in using the method and that it cannot be used in the on-site hardware. He was concerned about determining static weight immediately on site. However, in this instance, it is not necessary to determine the static weight on site and it has been attempted to minimize the on-site hardware, burdening the off-site, general-purpose computer.

The operations necessary to this data-reduction process are all quite simple and straightforward, including the fitting of the dynamic axle load function, which should allow rapid and economical reduction.

Given the fitted dynamic axle load function, $f_{AX_k}(t)$, two other techniques appear worthy of evaluation for the determination of static weight:

1. Calculating the RMS value of the function, $f(t)$, over the defined interval of the function, $t \varepsilon [t_o, t_f]$, where t_o is the first sample (sensor) time and t_f is the last sample (sensor) time

2. Calculating the moment, $\overline{f(t)}$; i.e., an estimate of the static weight is determinable from:

$$\overline{W}_s \simeq \overline{f(t)} = \frac{\int_{t_o}^{t_f} f^2(t)\, dt}{\int_{t_o}^{t_f} f(t)\, dt} .$$

<u>Vehicle Classification</u>

The data-reduction process will provide, for each truck, the distances between axles and the total number of axles. It will also provide the total static weight of each axle. Logic and tabular axle distance and axle weight data can be established in the data-reduction program which will allow determination of the truck type, as illustrated in Table 8, within a given confidence interval.

Table 8. Truck classification tabulation.

Truck Type	Truck Description
2P	2-axle panels or pickups
2000	2-axle, 4-tired truck
2D'	2-axle, 6-tired truck
300	3-axle truck
2S1	2-axle truck and 1-axle semitrailer
2S2	2-axle truck and 2-axle semitrailer
3S2	3-axle truck and 2-axle semitrailer
2S11	2-axle truck and 1-axle semitrailer/ 1-axle trailer
2002	2-axle truck and 2-axle trailer
3001	3-axle truck and 1-axle trailer
3002	3-axle truck and 2-axle trailer
2001	2-axle truck and 1-axle trailer
2003	2-axle truck and 1-axle trailer
2S12	2-axle truck, 1-axle semitrailer/ 2-axle trailer
2S22	2-axle truck, 2-axle semitrailer/ 2-axle trailer
3003	3-axle truck and 3-axle trailer
3022	3-axle truck, 2-axle trailer and 2-axle trailer
3S3	3-axle truck and 3-axle semitrailer
3S1	3-axle truck and 1-axle semitrailer
3S12	3-axle truck, 1-axle semitrailer/ 2-axle trailer
2022	2-axle truck, 2-axle trailer and 2-axle trailer
3S21	3-axle truck, 2-axle semitrailer/ 1-axle trailer
2S13	2-axle truck, 1-axle semitrailer/ 3-axle trailer
2S23	2-axle truck, 2-axle semitrailer/ 3-axle trailer
3S23	3-axle truck, 2-axle semitrailer/ 3-axle trailer

The weight per axle will not provide total certainty in establishing whether an axle is equipped with single tires or dual tires, e.g., between a 2S and a 2D. A dual-equipped, 2-axle empty truck would possibly be classified as a 2S rather than a 2D. Such a classification affects any statistical classification analysis that would be made from such data. However, there is no easily implementable means to distinguish between single-tired axles and dual-tired axles. Other ambiguities are likely to arise which will cause incorrect classification of a truck. Classic examples of trucks which will create problems in classification and reduction processing are:

1. Logging trucks which are of the tractor-trailer configuration. However, since the linkage from the tractor to the dolly is created by the log payload, no discernable signal is expected to occur between the tractor and the dolly. As a result, the raw data record will indicate two separate vehicles. Special logic in the reduction computer program(s) is necessary to properly handle this problem.

2. Utility trucks which pull wooden power or telephone poles on a dolly. The tractor is usually a type 3D equipped to pull a pole-connected dolly. This situation is similar to the logging truck and will require special logic to process.

All of the necessary criteria have not been included in the flow shown in Figure 35, nor have all possible truck types. This subroutine could also be used to collect classification and matching weight statistical data if it was desired.

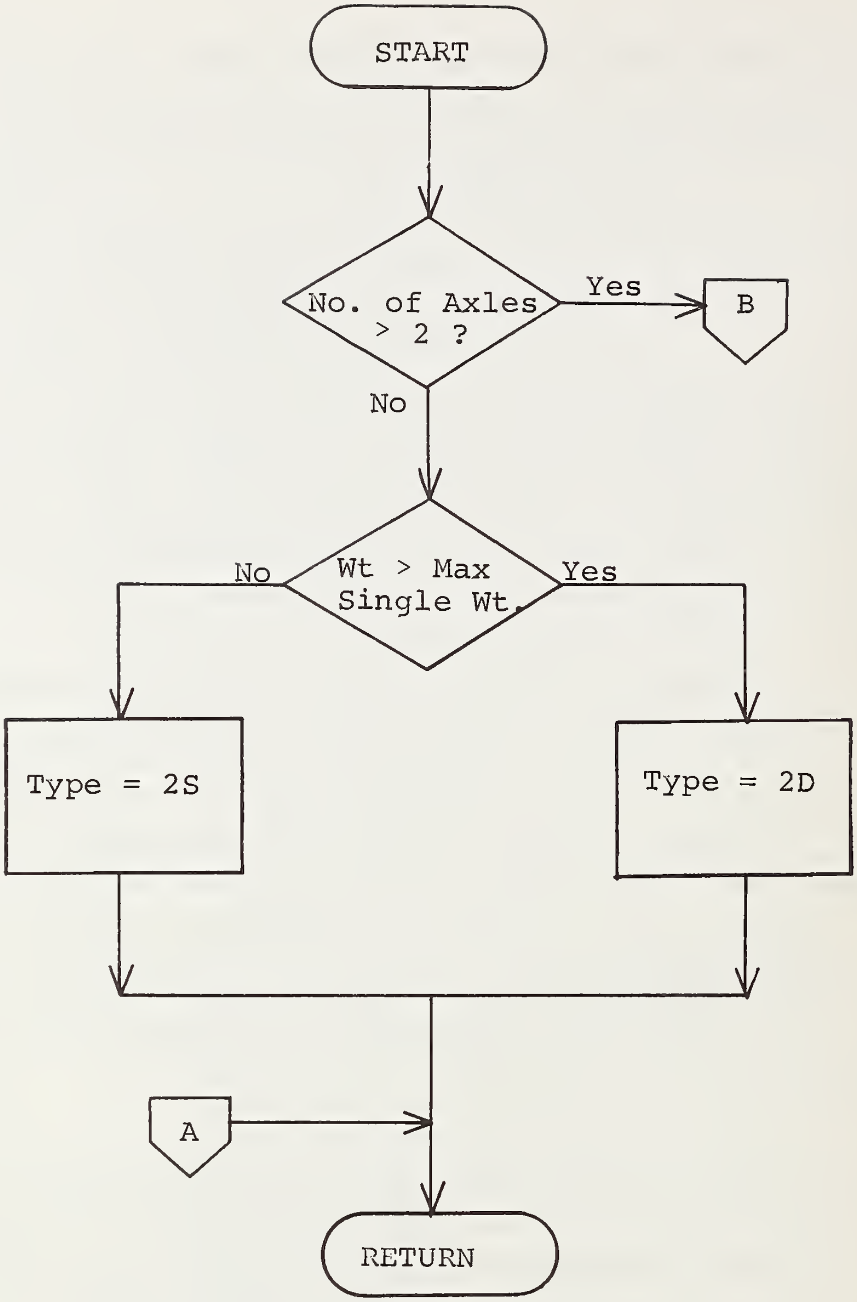


Figure 35. Example of classification subroutine flow.

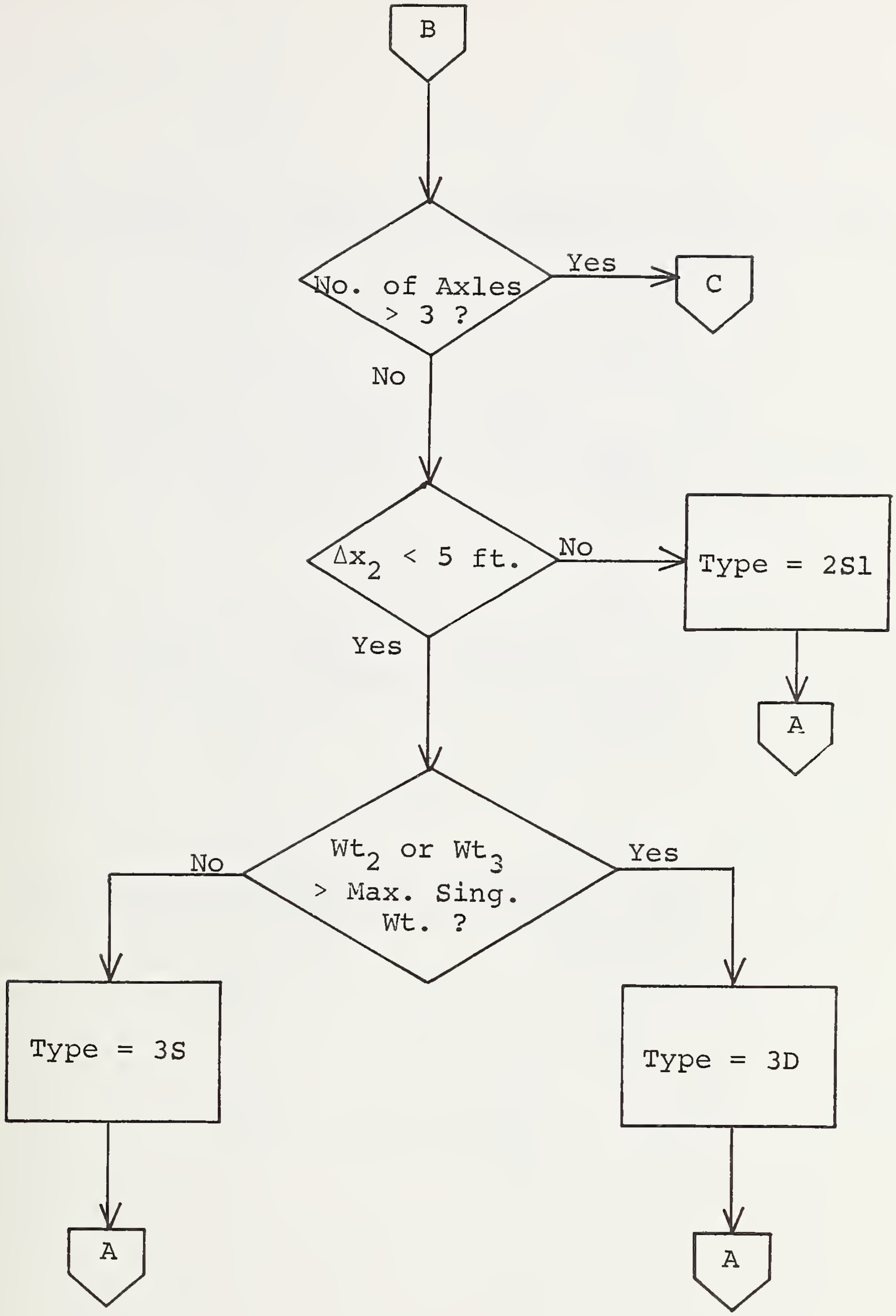


Figure 35. Example of classification subroutine flow. (cont.)

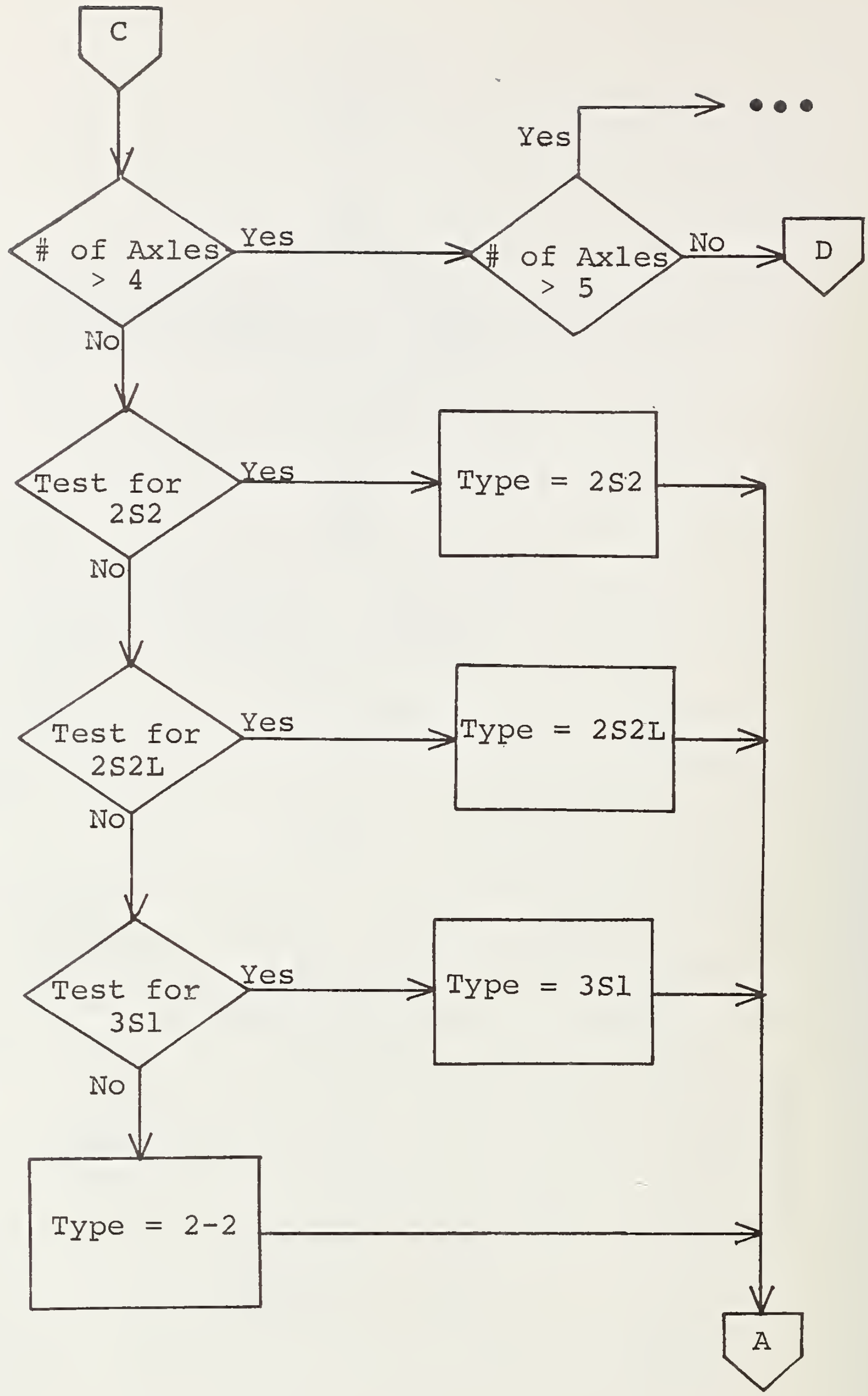


Figure 35. Example of classification subroutine flow. (cont.)

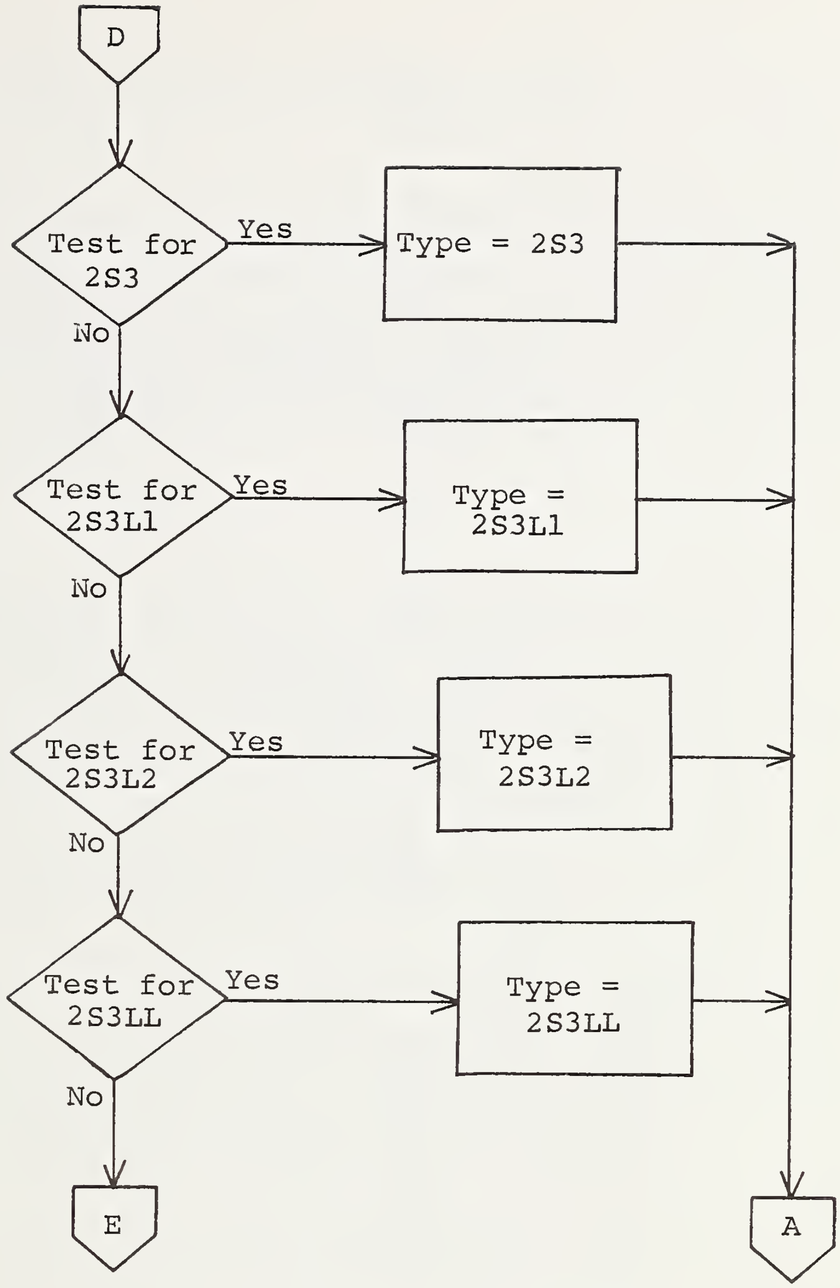


Figure 35. Example of classification subroutine flow. (cont.)

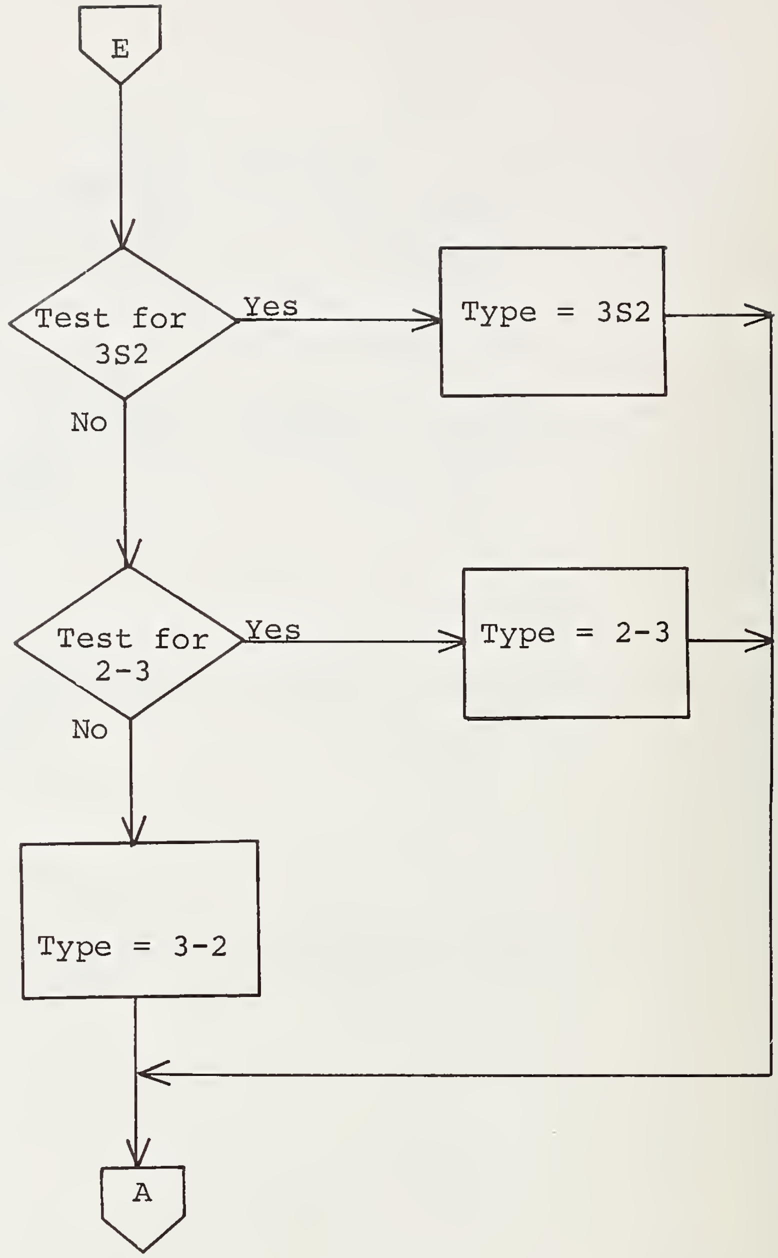


Figure 35. Example of classification subroutine flow. (cont.)

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations presented herein are based on the information gained from the literature search effort, direct analysis of the problem involved, and information from an independent investigation on the use of seismic sensors performed by the investigators.

CONCLUSIONS

The most fundamental conclusion reached by these investigators is that any developer of an "in-motion" weighing system must be, or become, completely familiar with the dynamic interaction between a vehicle, its components, and a roadway or bridge deck. Without such knowledge, any effort to develop such a device will, more than likely, end in failure or some degree of failure.

As a corollary to the first conclusion, it was concluded that, in order to obtain an accurate static weight, it is necessary to obtain a somewhat more accurate representation of the dynamic pavement load behavior of a vehicle.

With regard to potential sensors, there are two basic forms:

1. Direct

2. Indirect.

In neither case was there a single sensor capable of acquiring all of the necessary variables. This evaluation was

based on the ability to reduce the set of specified variables to a minimum set of five from which the balance could be derived.

Of the indirect forms open to investigation in this study, accelerometer measurements and seismic measurements, only seismic sensors appear potentially usable. However, available evidence is insufficient for bridge dynamic load usage to make a well-founded decision on their feasibility of use. A testing and evaluation effort is necessary to provide a sound basis for feasibility determination. Available evidence is extremely favorable, but inconclusive. Further, seismic sensors appear to provide an effective and economical means of collecting dynamic behavior data on bridges under dynamic loadings.

In the area of direct-contact-type sensors, a total of nine potential load-sensing transducers were identified in two geometric designs that are in varying levels of development. Some of these transducers were based on the identification of two pressure-sensitive elastomers. Both of the geometric designs for all nine transducers should have a low production cost.

It is not possible with a direct-contact-type transducer to obtain a representative sample of a truck axle's dynamic load function from a single sample (weighing) while in motion. Considering the types of trucks, their suspension system frequencies, which dominate their dynamic behavior, and their speed envelopes, a nominal minimum of six axle load samples are necessary to obtain a characterizing representation of their dynamic load functions. Further, in

order to obtain a well-behaved sampling and increase static weight accuracy, the installation of the multiple transducers should be made in the smoothest, flattest (no slopes in order to prevent roll) portion of the bridge deck, and at least 35 ft from the nearest surface perturbation, such as an expansion joint, beginning of span, etc., to allow damping of the truck excitation from the deck perturbations. This includes the need for a smooth surface over the transducers.

The simplest and most reliable technique to establish lane definition is to instrument those lanes in which truck traffic occurs or is dominant. The lanal PVD package can be produced in the form of an economical, compact, small, and light-weight package. A total of four potential PVD packages were identified that could be used to support the load sensors in acquiring the necessary variables. A small and compact lanal processing package can also be produced which is installable beneath the deck under the instrumented lane.

The central on-site processing hardware for all lanal package output can be produced in a universal form, which will allow interchangeability of the direct-contact type of load-sensing transducers. Such an approach provides for uniform output for off-site data reduction, regardless of the transducer used to acquire the dynamic load signal.

The use of off-line data-reduction facilities, i.e., a large general-purpose computer, will allow the use of more powerful numerical techniques than have been used in the past to determine static axle weight from dynamic load data.

This will provide more accurate and consistent determination of static vehicle weights. Further, the necessary data-reduction computer programs can be developed in a straightforward manner and are well within the state-of-the-art.

The cost of developing each of the necessary hardware packages would be on the order of $10,000.

RECOMMENDATIONS

If serious interest exists in the use of seismic sensors, it is recommended that a small test and evaluation effort be sponsored to acquire the necessary information to make a sound decision on the feasibility of using these sensors to determine dynamic load data from in-motion vehicles.

In the event that the determination on the use of seismic sensors is deferred, or if it is determined that they are definitely unsuited, it is recommended that the direct-contact type of transducer be tested and evaluated in the order of the ranking presented in the report. Further, it is recommended that multiple-transducer lanal installations be used to collect dynamic load data, as presented earlier in this report. It is also recommended that any prototype developmental program be defined to allow the evaluation of more than one of the direct-load sensing transducers. In order to minimize the initial cost of a prototype system, it is recommended that the field evaluation be performed on an interstate highway bridge in a rural area. This would allow a single-lane installation of the load-sensing transducers, but would probably capture 90-96 percent of the truck population using the bridge.

It is strongly recommended that the CW-Doppler radar sensor proposed as the PVD be used, based upon the simplicity of its installation, its operating characteristics, the fact that it requires no special structure other than the bridge structure, its modest cost, and the ease with which it may be removed and reused.

For the purposes of developing a prototype, it is recommended that the universal acquisition and recording system concept be used. It allows a great deal of transducer flexibility and, consequently, significantly increases the probability of producing a satisfactory prototype system. A system which is designed around a specific transducer is an extremely risky investment, as has been demonstrated in many other efforts. It is also recommended that the system be fully digital and that the output be compatible to the reading ability of a large, off-site, general-purpose computer. Many such efforts in the past were plagued with the inability to process the collected data properly. It is also recommended that the on-site processing equipment be minimized by restricting its processing functions at the 2,000-lb (907-kg) discard test, for minimization of the on-site data storage media. Maximization of the off-site computer data-reduction processes is also recommended because of the flexibility inherent in computer software. It is much easier and cheaper to make modifications to computer software of this nature than to make modifications to the on-site hardware; also, it can generally be accomplished much faster. This also provides a higher probability of success in producing a prototype system, as well as minimizing hardware costs.

REFERENCES

(1) R.H. Murray, W.L.,Wood, and R. Brown, Traffic Sensor (Study) Program, Report No. U1-286602-F, Texas Instruments, Inc., Dallas, Texas, 1970.

(2) R. Ameigh, et al., A Study to Determine the Feasibility of Development of an Area Traffic Surveillance and Control System, Final Phase 1A Report, General Electric Co., February 1969.

(3) J.Z. Grayum, "Weighing Trucks on the Move," Commercial Car Journal, October 1965, pp. 86-89.

(4) A.P. Whittemore, et al., Dynamic Pavement Loads of Heavy Highway Vehicles, Report No. 105, National Cooperative Highway Research Program, Washington, D.C., 1970.

(5) Nasser I. Al-Rashid, Clyde E. Lee, and William P. Dawkins, A Theoretical and Experimental Study of Dynamic Highway Loading, Report No. 108-IF, University of Texas, Center for Highway Research, Austin, Texas, 1972.

(6) Clyde R. Herrick, Analytic Study of Weighing Methods for Highway Vehicles in Motion, N.C.A.R.P. Report No. 71, Washington, D.C., 1969.

(7) D.K. Blythe, J.A. Dearinger, and R.E. Puckett, "Research Report on Electronic Highway Scales for Weighing Trucks in Motion," Highway Research Record, No. 100, Highway Research Board, Washington, D.C., 1965, pp. 55-57.

(8) J.H. Havens, Development of an Electronic Means of Weighing Vehicles in Motion, Memorandum, Kentucky Department of Highways, June 1971.

(9) South Dakota Highway Commission, Dynamic Tests on a Rolled Beam Composite Continuous Span Bridge, South Dakota Department of Highways Report, Part II, October 1955.

(10) R.A. Graves, III, Special Interstate Truck Weight Study, Research Report No. 1-7, Georgia Department of Transportation, Atlanta, Ga., 1972.

(11) M.M. Alexander and R.E. Bowling, The Collection and Use of Truck Weight Data, Research Report No. 6902, Georgia State Highway Department, Atlanta, Ga., 1970.

(12) Instrument Society of America, ISA Transducer Compendium, Glenn F. Harvey, Ed., Parts 1 and 2, IFI/Plenum, New York, N.Y., 1973.

(13) R.A. Weiss, Detection Capability of a Strain Sensitive Cable Sensor, U.S. Army, WES Technical Report M-73-6, November 1973.

(14) L.E. Wilson and J.C. Ravis, Development of a P/M Line Sensor, USAF, RADC Report TR-73-165, June 1973.

(15) R.C. McMaster and M.L. Rhoten, Measurement of Mechanical Stresses Using Piezoelectric Crystals, Ohio State University, Engineering Experiment Station, Columbus, Ohio, 1972.

(16) B.E. Bourland, S.K. Clark, and R.N. Dodge, Development of Textile Cord Load Transducer, ORA Project Report 01193-1-T, University of Michigan, College of Engineering, Ann Arbor, Mich., 1968.

(17) T. Kovattana and A. Rosengreen, Intrusion-Detection Devices and Systems for Air Base Security, RADC Report TR-73-246, Stanford Research Institute, August 1973.

(18) J.E. Bryden and J.A. Monda, Evaluation of the Viatec Axle Weight Analyzer, Research Report 25-2, New York State Department of Transportation, July 1971.

(19) E. Robinson and D.E. Willis, Seismic Signatures of Pneumatic-Tired Vehicles, University of Michigan, Willow Run Laboratories, Acoustics and Seismics Laboratory, Ann Arbor, Michigan, 1959.

(20) H.B. Sutherland, "A Study of the Vibrations Produced in Structures by Heavy Vehicles," Highway Research Board Proceedings, Washington, D.C., 1950, pp. 406-419.

(21) F.J. Tanis, Seismic Studies - Part 1: Seismic and Acoustic Data Processing for Determination of CPA and MR Vehicle Tracking Parameters, U.S. Army Mobility Equipment Research and Development Center, Final Report 1025006-F(1), March 1974.

(22) J.R. Curro, Jr., Site Characterization of Vehicle Signature Study Sites, General Motors Proving Grounds, Milford, Michigan, Miscellaneous Paper M-73-3, Mobility and Environmental Systems Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., April 1973.

(23) L.E. Link, Jr., and W.F. Marcuson, III, Mapping Seismic Response Characteristics of Complex Terrain, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., 1972.

(24) L.E. Link, H.W. West, and B.O. Benn, Dry Season Seismic Propagation Mapping of Sensor Test Grids, Part 1, USATTC Report No. 7204002, U.S. Army Tropic Test Center, Ft. Clayton, Canal Zone, April 1972.

(25) K.J. Murphy and K. Ikrath, Analysis of a "Seismic Fence" for Intrusion Detection, Research and Development Technical Report, ECOM-2848, U.S. Army Electronics Command, Ft. Monmouth, N.J., May 1967.

(26) G. Swift and W.M. Moore, Investigation of the Applicability of Acoustic Pulse Velocity Measurements to Evaluation of Quality of Concrete in Bridge Decks, Texas Highway Department, Research Report 130-7, August 1971.

(27) J.B. Karrh and T.R. Douglass, Investigation of Traffic Induced Vibrations and Their Effect on the Concrete Decks of Highway Bridges, HPR Report No. 60, University of Alabama, Tuscaloosa, Ala., December 1971.

(28) W.J. Cheesman, "Dynamic Testing of Concrete with the Soniscope Apparatus," Highway Research Board Proceedings, Highway Research Board, Washington, D.C., 1949, pp. 176-183.

(29) W.M. Moore, An Instrument for Detecting Delamination in Concrete Bridge Decks, Research Report No. 130-4, Texas Transportation Institute, College Station, Texas, 1970.

(30) W.E. Brownfield, "Nondestructive Testing of Concrete by Wave Velocity Methods: A Laboratory and Field Study," Highway Research Record, No. 378, Highway Research Board, Washington, D.C., 1972, pp. 12-19.

(31) J.M. Phelps and T.R. Cantor, "Detection of Concrete Deterioration Under Asphalt Overlays by Microseismic Reduction," Highway Research Record, No. 146, Highway Research Board, Washington, D.C., 1966, pp. 34-49.

(32) R.P. Murrman, et al., Vehicle Detection Classification Using Chemical Sensors, Special Report 18, U.S. Army, Cold Regions Research and Engineering Laboratory, Hanover, N.H., August 1972.

(33) R.J. Keith and S.T. Yan, "The Traffic Analyzer: An Instrument for the Automatic Measurement of Traffic Parameters," Australian Road Research Board Proceedings, Vol. 1, 1968, pp. 739-748.

(34) C.E. Minor, "Traffic Counting and Recording," Papers and Discussions, Convention Group Meetings, American Association of State Highway Officials, 1967, pp. 153-156.

(35) R. Gaebele, Low Light Level Television System for Intrusion Detection, GTE Sylvania, Inc., Report, Mountain View, Calif., April 1971.

(36) M.K. Mills, "Magnetic Gradient Vehicle Detector," Proceedings, 1973 VTG Conference, Institute of Electrical and Electronic Engineers, New York, N.Y., 1973.

(37) K. Ikrath and W.A. Schneider, "Communications Via Seismic Waves Employing 80-Hz Resonant Seismic Transducers," IEEE Transactions on Communication Technology, Vol. COM-16, No. 3, June 1968, p. 439.

APPENDIX A

KEYWORD LIST FOR AUTOMATED SEARCHES

The following list of keywords was developed for the automated searches using as basic references the "TRB Research Index Titles for 1972-1973" and the sensor list given in the original proposal to FHWA. Several refinements to the list were made. The list reproduced herein represents the final version of the Keyword List used for the HRIS searches. Further delimiters were inserted by NTIS to insure that no duplication of data would occur in the searches by NTIS and HRIS and that no classified data would be retrieved by the NTIS search.

<u>HRB Research Index Titles for 1972-1973</u>

Acoustic Measurement - Sensors
Acoustics - Sensors
Acquisition - Electronic data
Actuated Control - Vehicle & traffic
Actuators - Vehicle & traffic
Adhesion - Pavement & concrete
Adhesives - Pavement
Automatic Control - Vehicle sensing & detection
Bonding - Pavement
Bonding Strengths - Pavement
Bonds - Pavement
Conductivity - Pavement
Data Recorders - Electronic & digital
Data Recording - Electronic & digital
Detecting Devices
Detection
Detectors
Detectors/Traffic
Dynamic Characteristics - Trucks, truck wheels, truck suspension, truck tires, bridges
Dynamic Loading - Trucks, truck wheels, truck suspension, truck tires, bridges
Dynamic Loads - Trucks, truck wheels, truck suspension, truck tires, bridges
Dynamic Response - Trucks, truck wheels, truck suspension, truck tires, bridges
Dynamic Tests - Trucks, truck wheels, truck suspension, truck tires, bridges
Dynamometers

Electrical Measurements - Bridges, concrete, pavement
Electrical Resistance - Bridges, concrete, pavement
Electrical Resistivity Method - Bridges, concrete, pavement
Electrical Strain Gages - Bridges, concrete, pavement
Electronic Devices - Vehicle sensing, detection, measurement
Electronic Traffic Devices - Vehicle sensing, detection, measurement
Electronics - Vehicle sensing, detection, measurement
Electronics/Traffic - Vehicle sensing, detection, measurement
Excitation - Concrete, pavement
Field Measurements - Vehicle sensing, detection, measurement
Field Methods - Vehicle sensing, detection, measurement
Field Observation - Vehicle sensing, detection, measurement
Field Tests - Vehicle sensing, detection, measurement
Frequencies - Truck loadings/types/sensors, bridge dynamics and response
Frequency Distribution - Truck loadings/types/sensors, bridge dynamics & response
Frequency Response - Truck loadings/types/sensors, bridge dynamics & response
Gages - Traffic sensing
Geophysical Measurements - Seismic/ground shock & vibration
Harmonics - Bridge, bridge deck, trucks
Impulse Tests/Electrical - Concrete, pavement, bridges
Infrared Detectors
Infrared Spectrophotometers
Infrared Spectroscopy
In-Situ Methods - Vehicle detection, sensing, measurement
Instrumentation - Real-time data acquisition

Lasers as Sensors
Loops/Electrical - Vehicle detection/sensing, measurement
Magnetic Vehicle Detectors
Measuring - Vehicle dynamics & loading
Measuring Instruments - Vehicle dynamics & loading
Monitoring - Vehicle dynamics & loading
Monitors - Vehicle dynamics & loading
Moving Vehicles - Detection, sensing, measurement
Noise/Spurious Signals - Traffic sensing
Optical Scanners
Photoelectric Cells
Piezometers
Plate Bearing Tests - Vehicle dynamics & loading
Pressure Measurement - Vehicle dynamics & loading
Pressure Sensors - Switch actuators & vehicle dynamics & loading
Radar
Radar Applications
Radar Vehicle Detector
Recording Instruments - Real-time/digital/periodic
Recording Systems - Real-time/digital/periodic
Reflectance - Trucks, vehicles, active & passive sensors
Reflectivity - Trucks, vehicles, active & passive sensors
Remote Directional Detector
Remote Directional Measurement
Remote Distance Measuring Equipment
Remote Sensing
Resistance - Concrete, bridges, pavement
Resistivity - Concrete, bridges, pavement
Resonance - Concrete, bridges, pavement
Resonant Frequencies - Concrete, bridges, pavement

Seismic Investigations - Concrete, structures, pavement, bridges
Seismic Properties - Concrete, structures, pavement, bridges
Seismic Waves - Concrete, structures, pavement, bridges
Seismometers - Concrete, structures, pavement, bridges
Sensors
Shock Attenuation - Pavement
Shock/Mechanics - Concrete, pavement, bridges
Shock Waves - Concrete, pavement, bridges
Sonics - Sensing, vehicles, concrete, pavement
Soniscope
Spectrometers - Sensing
Spectrophotometers - Sensing
Speed Indicators
Speed - Sensing, measurement
Speed Studies - Sensing, measurement
Strain Gages
Strain Measurement - Bridges, pavement
Strain Rate - Bridges
Tensiometers
Testing Equipment - Bridge dynamics/vehicle traffic sensing, detection, measurement, recording
Tires - Truck, dynamics, dynamic loading, load distribution
Traffic Actuated Detectors
Traffic Control Devices
Traffic Platooning
Transducers
Transmittance
Transmitters
Truck Effects/Bridges
Truck Platooning

Trucks - Dynamics, dynamic loading, sensing, classification, detection, measurement
Ultrasonics
Ultrasonic Testing
Vehicle Characteristics - Dynamics, dynamic loading, sensing, classification, detection, measurement
Vehicle Classification
Vehicle Detecting Equipment
Vehicle Dynamics
Vehicle Lane Occupancy
Vehicle Lateral Placement
Velocity Measurement - Vehicles
Velocity Spectrum of Vehicles
Vibration Damping - Bridges, concrete, pavement
Vibration Meters - Bridges, concrete, pavement
Vibrations - Bridges, concrete, pavement
Weighing Equipment
Weight Indicators
Weight Measurement
Wheel Base - Trucks
Wheel Load - Trucks
Wheel Load Distribution - Trucks
Wheel Path - Trucks
Wheels - Trucks

Sensor List Taken From Original Proposal

Ground Shock Detection

Conductance Pads

Video Sensors

Acoustic Sensors/Acoustic Doppler Sensors/Passive/Active

Infrared Sensors

Light Sensors-Photoelectric Cells/Light-Emitting Diodes

Reflective Sensors

Fibre Optical Sensing

Radar (RF) Sensors/Doppler Radar Sensors

Transducers, Displacement

- Reactive
- Self-Generating
- Magnetometer

Pneumatic Sensors/Pressure Transducers

APPENDIX B

SELECTED BIBLIOGRAPHY

Alexander, M.M., Jr., and Bowling, R.E., The Collection and Use of Truck Weight Data, Research Report No. 6902, Georgia State Highway Department, Atlanta, Ga., 1970.

Alexander, M.M., and Graves, R.A., Determination of the Lanal Distribution of Truck Traffic on Freeway Facilities, Research Report No. 7001, Georgia State Highway Department, Atlanta, Ga., 1971.

Al-Rashid, Nasser I., Lee, Clyde E., and Dawkins, William P., A Theoretical and Experimental Study of Dynamic Highway Loading, Report No. 108-IF, University of Texas, Center for Highway Research, Austin, Texas, 1972.

Ameigh, R., et al., A Study to Determine the Feasibility of Development of an Area Traffic Surveillance and Control System, Final Phase 1A Report, General Electric Co., February 1969.

Bigelow, Nelson, Jr., "Seismograph Operations by Maine State Highway Commission," Highway Research Record, No. 81, Highway Research Board, Washington, D. C., 1965, pp. 9-15.

Biggs, John M., Suer, Herbert S., and Louw, J.M., Vibration Measurements on Simple Span Bridges, Massachusetts Institute of Technology, Joint Highway Research Project, Research Report No. 19, Cambridge, Mass., 1956.

Blackmore, D.H., and Howe, J. D. G. F., Using SYX-RRL Vehicle Counters Number 4A and 4B in Tropical Countries, RRL Report No. LR 385, Road Research Laboratory, Crawthorne, Berks., England, 1971.

Blair, B.E., and Duvall, W.I., Evaluation of Gages for Measuring Displacement, Velocity, and Acceleration of Seismic Pulses, U.S. Department of the Interior, Bureau of Mines, Pittsburgh, Pa., 1954.

Blythe, D.K., Dearinger, J.A., and Puckett, R.E., "Research Report on Electronic Highway Scales for Weighing Trucks in Motion," Highway Research Record, No. 100, Highway Research Board, Washington, D. C., 1965, pp. 55-57.

Bollinger, G.A., Blast Vibration Analysis, Southern Illinois University Press, Carbondale, Ill., 1971.

Bourland, B.E., Clark, S.K., and Dodge, R.N., Development of Textile Cord Load Transducer, ORA Project Report 01193-1-T, University of Michigan, College of Engineering, Ann Arbor, Mich., 1968.

Brickman, A.N., Wambold, J.C., and Zimmerman, J.R., "An Amplitude Frequency Description of Road Roughness," Improving Pavement and Bridge Deck Performance, Special Report 116, Highway Research Board, Washington, D. C., 1971, pp. 53-67.

Brownfield, W.E., "Nondestructive Testing of Concrete by Wave Velocity Methods: A Laboratory and Field Study," Highway Research Record, No. 378, Highway Research Board, Washington, D.C., 1972, pp. 12-19.

Bryden, J.E., and Monda, J.A., Evaluation of the Viatec Axle Weight Analyzer, Research Report 25-2, New York State Department of Transportation, July 1971.

Carr, B.W., Jr., and Rizenbergs, R.L., Development of an Electronic Means of Weighing Vehicles in Motion, Research Report No. 307, Kentucky Department of Highways, Division of Research, Lexington, Ky., April 1971.

Cheesman, W.J., "Dynamic Testing of Concrete with the Soniscope Apparatus," Highway Research Board Proceedings, Highway Research Board, Washington, D. C., 1949, pp. 176-183.

Claerbout, Jon F., "Synthesis of a Layered Medium from Its Acoustic Transmission Response," Geophysics, Vol. 33, No. 2, April 1968, pp. 264-269.

Corbett, D.A., et al., Evaluation of Pressure Cells Used for Field Measurements of Lateral Earth Pressure on Retaining Walls, Research Report No. 169-1, Texas Transportation Institute, College Station, Texas, 1971.

Corson, R.H., "A New Gauge for the Measurement of Internal Strains in Concrete," Concrete and Construction Engineering, Vol. LX, No. 12, December 1965, p. 437.

Courage, Kenneth G., "Some Electronic Measurements of Macroscopic Traffic Characteristics on a Multilane Freeway," Highway Research Record, No. 279, Highway Research Board, Washington, D. C., 1969, pp. 107-118.

Crawford, J.C., "A Peizoelectric Field-Effect Strain Gage," Experimental Mechanics, April 1971, p. 145.

Csagoly, P.F., Campbell, T.I., and Agarwal, A.C., Bridge Vibration Study, MTC Report No RR181, Ontario Ministry of Transportation and Communications, Downsview, Ont., Canada, 1972.

Curro, J.R., Jr., Site Characterization of Vehicle Signature Study Sites, General Motors Proving Grounds, Milford, Michigan, Miscellaneous Paper M-73-3, Mobility and Environmental Systems Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., April 1973.

Damberg, F., Possibilities of Error and Possibilities of Utilization of Various Methods for the Measurement of Dynamic Wheel Forces or Ground Forces on Vehicles, Report No. FTD-HT-23-1255-71, U.S. Air Force, Foreign Technical Division, May 1970.

Dyson, D.F., and McDevitt, W., "Engineering Refraction Seismic Surveys," Australian Road Research Board Proceedings, Vol. 2, 1966, pp. 1251-1254.

Edgerton, Roy D., and Beecroft, Gordon W., "Dynamic Studies of Two Continuous Plate-Girder Bridges," Highway Research Bulletin, No. 124, Highway Research Board, Washington, D.C., 1956, pp. 33-46.

Edholm, S., "Methods of Traffic Measurement - Determination of Number and Weight of Vehicles," Highway Research Bulletin, No. 338, Highway Research Board, Washington, D.C., 1962, pp. 81-99.

Fisher, T.W., and Hickens, H.G., Measuring Dynamic Vehicle Loads, National Academy of Sciences, National Research Council, St. Louis, Mo., May 1962.

Fogelson, D.E., and Johnson, C.F., Calibration Studies of Three Portable Seismographs, Report of Investigations No. 6009, U.S. Department of the Interior, Bureau of Mines, Washington, D. C., 1962.

Foster, George M., "Vibration and Deflection of Rolled-Beam and Plate Girder Bridges," Highway Research Bulletin, No. 124, Highway Research Board, Washington, D.C., 1956, pp. 79-110.

Gaebele, R., Low Light Level Television System for Intrusion Detection, GTE Sylvania, Inc., Report, Mountain View, Calif., April 1971.

Grainger, J.W., The Types of Vehicles Which Have Excessive Axle Loads, RRL Report No. LR 380, Road Research Laboratory, Crawthorne, Berks., England, 1971.

Graves, R.A., III, Special Interstate Truck Weight Study, Research Report No. 1-7, Georgia Department of Transportation, Atlanta, Ga., 1972.

Grayum, J.Z., "Weighing Trucks on the Move," Commercial Car Journal, October 1965, pp. 86-89.

Ham, R., "Area Traffic Control in West London, Vehicle Counting Detectors," Traffic Engineering and Control, Vol. 11, No. 4, August 1969, pp. 172-176.

Harbour, J.H., Electronic Computer Program for the W-6 Loadometer Truck Weight Table, California Division of Highways Report.

Havens, J.H., Development of an Electronic Means of Weighing Vehicles in Motion, Memorandum, Kentucky Department of Highways, June 1971.

Hayes, John M., and Sharownis, John A., "Vibration Study of Three-Span Continuous I-Beam Bridges," Highway Research Bulletin, No. 124, Highway Research Board, Washington, D.C., 1956, pp. 47-78.

Heathington, Kenneth W., and Tutt, Paul R., "Estimating the Distribution of Axle Weights for Selected Parameters," Highway Research Record, No. 189, Highway Research Board, Washington, D.C., 1967, pp. 44-78.

Hermont, A.J., "Is Seismic Energy of Diagnostic Value?" Geophysics, Vol. 34, No. 2, April 1969, pp. 196-212.

Herrick, Clyde R., Analytic Study of Weighing Methods for Highway Vehicles in Motion, N.C.A.R.P. Report No. 71, Washington, D.C. 1969.

Hopkins, John B., Development of Anticipatory Automobile Crash Sensors, Transportation Systems Center, Cambridge, Mass., 1971.

Hopkins, R.C., and Boswell, H.H, "Methods for Measuring Load Transfer Through Vehicle Tires to the Road Surface," Highway Research Board Proceedings, 1957, pp. 240-253.

Humphreys, Jack B., "Effect of Trucks on the Urban Freeway," Highway Research Record, No. 308, Highway Research Board, Washington, D.C., 1970, pp. 62-75.

Highway Research Board, Non Destructive Testing of Concrete, Bibliography 33, Washington, D.C., 1963.

Ikrath, K., and Schneider, W.A., "Communications Via Seismic Waves Employing 80-Hz Resonant Seismic Transducers," IEEE Transactions on Communication Technology, Vol. COM-16, No. 3, June 1968, p. 439.

Ingham, C.E., "The Measurement of Young's Modulus by Seismic Methods," Fifth Australian - New Zealand Conference on Soil Mechanics and Foundation Engineering.

Instrument Society of America, ISA Transducer Compendium, Glenn F. Harvey, Ed., Parts 1 and 2, IFI/Plenum, New York, N.Y., 1973.

Jones, R., "Non-Destructive Testing of Roads and Structures," Papers, Public Works and Municipal Services Congress, No. 18, 1956.

_____, "Interpretation of Surface Vibration Measurements," Proceedings, Symposium of Testing of Roads and Runways, Amsterdam, Neth., 1959, pp. v-1 v-16.

_____, "Testing of Concrete by Ultrasonic-Pulse Technique," Highway Research Board Proceedings, Washington, D.C., 1953, pp. 258-275.

Jones, R., and Gatfield, E.N., Testing Concrete by an Ultrasonic Pulse Technique, Road Research Technical Paper No. 34, Road Research Laboratory, Her Majesty's Stationery Office, London, England, 1955.

Kansas Highway Commission, Truck Weight and Vehicle Classification Study, Topeka, Kans., 1960.

Karrh, J.B., and Douglass, T.R., Investigation of Traffic Induced Vibrations and Their Effect on the Concrete Decks of Highway Bridges, HPR Report No. 60, University of Alabama, Tuscaloosa, Ala., December 1971.

Kent, Malcolm F., and Stevens, Hoy, "Dimensions and Weights of Highway Trailer Combinations and Trucks," Highway Research Record, No. 26, Highway Research Board, Washington, D.C., 1963, pp. 24-65.

Keith, R.J., "An Experimental Photoelectric Vehicle Detector Operating from an Ambient Light Source," Australian Road Research Board Proceedings, Vol. 1, 1966, pp. 690-696.

Keith, R.J., and Yan, S.T., "The Traffic Analyzer: An Instrument for the Automatic Measurement of Traffic Parameters," Australian Road Research Board Proceedings, Vol. 1, 1968, pp. 739-748.

Keith, R.J., "An Instrument for the Pulse Measurement of Vehicle Speed," Australian Road Research Board Proceedings, Vol. 1, 1968, pp. 785-790.

Kibbee, G.W., Measurement of the Dynamic Tire Forces of a Large Truck, Report No. 21, Indiana Engineering Experiment Station, Joint Highway Research Project, Purdue University, Lafayette, Ind., September 1965.

Klijnhout, J.J., "An Automatic Data Logger System for Traffic Measurements," Traffic Engineering and Control, Vol. 10, No. 8, December 1968, pp. 435-436.

Kovattana, T., and Rosengreen, A., Intrusion-Detection Devices and Systems for Air Base Security, RADC Report TR-73-246, Stanford Research Institute, August 1973.

Kubiak, E.J., and Jacobsen, F.K., Vehicle-In-Motion Weighing Experiment at Restored AASHO Road Test Facility, State of Illinois Report IHR-28, July 1971.

Lacoss, R.T., Kelly, E.J., and Toksoz, M.N., "Estimation of Seismic Noise Structure Using Arrays," Geophysics, Vol. 34, No. 1, February 1969, pp. 21-38.

Lee, C.E., and Al-Rashid, N.E., A Portable Electronic Scale for Weighing Vehicles in Motion, University of Texas, Center for Highway Research, Research Report No. 54-1F, Austin, Texas, April 1968.

Lee, J.A.N., and Windover, L., Highway Bridge Vibration 4. The Vibration of Continuous Highway Bridges, O.J.H.R.P. Report No. 40, Ontario Joint Highway Research Programme, Queens University, Department of Civil Engineering, Kingston, Ont., Canada, 1966.

Lee, R.D., Intruder Detection System, Patent Application N72-21161, February 1971.

_____, Metallic Intrusion Detector System, Patent N-70-41949, 1970.

Lessem, A.S., Dynamics of Wheeled Vehicles, Report No. 2, Implementation of Wiener-Bose Theory and Application to Ride Dynamics, Technical Report No. M-68-1, U.S. Army Materiel Command, U.S. Army Waterways Experiment Station, Vicksburg, Miss., March 1971.

Link, L.E., Jr., and Marcuson, W.F., III, Mapping Seismic Response Characteristics of Complex Terrain, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., 1972.

Link, L.E., West, H.W., and Benn, B.O., Dry Season Seismic Propagation Mapping of Sensor Test Grids, Part 1, USATTC Report No. 7204002, U.S. Army Tropic Test Center, Ft. Clayton, Canal Zone, April 1972.

Liston, L.L., and Bielak, S.F., "Comparison of Empty and Gross Weights of Commercial Vehicles," Highway Research Record, No. 26, Highway Research Board, Washington, D.C., 1963, pp. 1-23.

Lowe, D.S., "Multispectral Scanning Systems: Their Features and Limitations," Highway Research Record, No. 421, Highway Research Board, Washington, D.C., 1972, pp. 22-32.

Lynnworth, L.C., and Patch, D.R., "New Sensors for Ultrasound: Measuring Temperature Profiles," Materials Research and Standards, Vol. 10, No. 8, August 1970, pp. 6-11.

Lynnworth, L.C., and Bradsha, J.E., "Magnetostriction Transducers for Acoustic Emission, Impulse, Vibration and Noise Analysis," Materials Research and Standards, Vol. 11, No. 3, March 1971, pp. 33-35.

Mailer, Hugh, "Pavement Thickness Measurement Using Ultrasonic Techniques," Highway Research Record, No. 378, Highway Research Board, Washington, D. C., 1972, pp. 20-28.

Maryland State Roads Commission, Bureau of Traffic, 1961 Truck Weight Vehicle Classification Study, 1961.

McCauly, M.L., et al., Shallow Seismic Techniques, California Division of Highways, Research Report CA-HY-MR-2951-1-73-18, California Business and Transportation Agency, Department of Public Works, Division of Highways, Materials and Research Department, June 1973.

McMahon, J.E., Bridge Expansion Joint Sealant, Interim Report, State of California Transportation Agency, Department of Public Works, Division of Highways, Bridge Department, June 1966.

McMaster, R.C., and Rhoten, M.L., Measurement of Mechanical Stresses Using Piezoelectric Crystals, Ohio State University, Engineering Experiment Station, Columbus, Ohio, 1972.

Meidav, Tsvi, "Hammer Reflection Seismics in Engineering Geophysics," Geophysics, Vol. 34, No. 3, June 1969, pp. 383-395.

_____, "Shear Wave Velocity Determination in Shallow Seismic Studies," Geophysics, Vol. 32, No. 6, December 1967, pp. 1041-1046.

Mendis, Douglas D., The Development of Algorithims for Analysis of Intrusion Sensor Activations by Automatic Processing Techniques, Research and Development Technical Report No. ECOM-4174, U.S. Army Electronics Command, Fort Monmouth, N.J., December 1973.

Mills, M.K., "Magnetic Gradient Vehicle Detector," Proceedings, 1973 VTG Conference, Institute of Electrical and Electronic Engineers, New York, N.Y., 1973.

Minor, C.E.,"Traffic Counting and Recording" Papers and Discussions, Convention Group Meetings, American Association of State Highway Officials, 1967, pp. 153-156.

Moavenzadeh, F., and McMaster, R.C., Potential Uses of Sonic and Ultrasonic Devices in Highway Construction, NCHRP Report 25, National Cooperative Highway Research Program, Washington, D.C., 1966.

Moore, H. Woodward, The Application of Geophysical Methods of Subsurface Explorations to Highway Engineering Problems, Bureau of Public Roads, Washington, D.C.

Moore, W.M., An Instrument for Detecting Delamination in Concrete Bridge Decks, Research Report No. 130-4, Texas Transportation Institute, College Station, Texas, 1970.

Moreley, Peter J., "Vehicle Detector Evaluation Study," Traffic Engineering and Control.

Morris, S.A.H., Amplifier Unit for Use with the TRRL Dynamic Weighbridge, Transportation and Raod Research Laboratory Report LR530, Crawthorne, Berks., England, 1973.

Murphy, K.J., and Ikrath, K., Analysis of a "Seismic Fence" for Intrusion Detection, Research and Development Technical Report, ECOM-2848, U.S. Army Electronics Command, Ft. Monmouth, N.J., May 1967.

Murphy, N.R., Jr., Dynamics of Wheeled Vehicles, Report No. 1, Mathematical Model for the Traversal of Rigid Obstacles by a Pneumatic Tire; Appendix B, Digital Implementation of Segmented Tire Model, Technical Report No. M-68-1, U.S. Army Materiel Command, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss. August 1969.

_____, Dynamics of Wheeled Vehicles, Report No. 3, A Statistical Analysis of Terrain-Vehicle-Speed Systems, Technical Report No. M-68-1, U.S. Army Materiel Command, U.S. Army Engineer Waterways Experiment Station, April 1971.

Murray, R.H., Wood, W.L., and Brown, R., Traffic Sensor (Study) Program, Report No. U1-826602-F, Texas Instruments, Inc., Dallas, Texas, 1970.

Murrman, R.P., et al., Vehicle Detection Classification Using Chemical Sensors, Special Report 18, U.S. Army, Cold Regions Research and Engineering Laboratory, Hanover, N.H., August 1972.

National Academy of Sciences - National Research Council, Road Test One-MD, Highway Research Board, Special Report 4, NRC Publication 227, 1952.

Nordlin, E.F., et al., A Report on the Development of a Truck Classification Counter, State of California Highway Transportation Agency, Department of Public Works, Division of Highways, Sacramento, Calif., October 1965.

_____, Vehicle Classifying Counter, California Division of Highways Report M&R No. 36346-1, Sacramento, Calif., November 1969.

Norman, O.K., and Hopkins, R.D., "Weighing Vehicles In Motion," Highway Research Bulletin, No. 50, Highway Research Board, Washington, D.C.

Nothstine, J.R., and Beauvais, F.N., "Laboratory Determination of Tire Forces," Proceedings, International Summer Meeting, Montreal, Canada, June 10-14, Society of Automotive Engineers, New York, N.Y., 1964.

Nunn, D.E., A Method of Recording Axle Load Sequences and Groupings, TRRL Report No. LR 568, Transportation and Road Research Laboratory, Crawthorne, Berks., England, 1973.

Orr, William, F., "Using the Portable Refraction Seismograph to Predict Rippability," Proceedings, College of the Pacific Annual Highway Conference, 1960, pp. 48-52.

Paterson, Iain M., "Focus on Traffic Engineering Instruments," Traffic Engineering and Control, Vol. 11, No. 9, January 1970, pp. 426-427.

Pahl, Juergen, "The Effect of Discrete Time Measurement on Speed Data," Highway Research Record, No. 349, Highway Research Board, Washington, D.C., 1971, pp. 1-12.

Phelps. J.M., and Cantor, T.R., "Detection of Concrete Deterioration Under Asphalt Overlays by Microseismic Reduction," Highway Research Record, No. 146, Highway Research Board, Washington, D.C., 1966, pp. 34-49.

Philco-Ford Corporation, Communications and Electronics Division, Dynamic Vehicular Weighing System, Final Report, June 1967.

Pizer, R.S., and Spinner, S., " An Apparatus for Determining the Actual Foot Print Area of Tires," Materials Research and Standards.

Potocki, F.P., A Portable Wheel-Weighing Unit and Data Recorder, RRL Report No. LR 391, Road Research Laboratory, Crawthorne, Berks., England, 1971.

Potter, T.F., and Roden, R.B., "Seismic Noise Estimation Using Horizontal Components," Geophysics, Vol. 32, No. 4. August 1967, pp. 617-632.

Quinn, B.E., and Van Wyk, R., "A Method for Introducing Dynamic Vehicle Loads into Design of Highways," Highway Research Board Proceedings, Washington, D.C., 1961, pp. 111-122.

Reggia, R., MARDS Antenna Design for Seismic Detection Systems, Harry Diamond Laboratory Report, August 1972.

Ricker, E.R., and Fox, R.W., "Weighing Vehicles in Motion," Papers and Discussions, Convention Group Meetings, American Association of State Highway Officials, 1967, pp. 147-152.

Rivlin, R.S., and Steele, T.R., The Mechanics of Tires, Lehigh University, Bethlehem, Pa., December 1970.

Robinson, E., and Willis, D.E., Seismic Signatures of Pneumatic-Tired Vehicles, University of Michigan, Willow Run Laboratories, Acoustics and Seismics Laboratory, Ann Arbor, Michigan, 1959.

Roden, Robert B., "Seismic Experiments with Vertical Array," Geophysics, Vol. 33, No. 2, April 1968, pp. 270-284.

Scheffey, Charles F., "Dynamic Load Analysis and Design of Highway Bridges," Highway Research Bulletin, No. 124, Highway Research Board, Washington, D.C., 1956, pp. 16-32.

Schneeberger, E.F., and Hayman, R.A., "A Pulsed Doppler Radar Experiment for Highway Traffic Research," Highway Research Record, No. 308, Highway Research Board, Washington, D.C., 1970, pp. 92-104.

Scholer, Charles F., Performance of Ultrasonic Equipment for Pavement Thickness Measurement and Other Highway Applications, Purdue University, Lafayette, Ind., July 1970.

Scholer, C.F., and Pavlovich, R.D., Evaluation of the Performance of Ultrasonic Equipment for Pavement Thickness Measurement, Joint Highway Research Project, Purdue University, Lafayette, Ind., January 1969.

Scordelis, A.C., and Meyer, C., Wheel Load Distribution in Concrete Box Girder Bridges, Report No. SESM-69-1, College of Engineering, Office of Research Services, University of California, Berkeley, Calif., January 1969.

SDS Data Systems, A Data Acquisition System for Monitoring the Physical Phenomena of Highway Bridges in Service, 1967.

Seddon, P.A., "Another Look at Platoon Dispersion, 3. The Reccurrence Relationship," Traffic Engineering and Control, Vol. 13, No. 10, February 1972, pp. 442-444.

_____, "Another Look at Platoon Dispersion, 1. The Kinematic Wave Theory," Traffic Engineering and Control, Vol. 13, No. 8, December 1971, pp. 332-336.

Sheriff, R.E., "Glossary of Terms Used in Geophysical Exploration," Geophysics, Vol. 33, No. 1, February 1968, pp. 181-228.

Smith, M.E., et al., Deflection of Moving Tires, Report No. 3, Center-Line Deflection Studies Through July 1963, Technical Report No. 3-516, U.S. Army Materiel Command, U.S. Army Waterways Experiment Station, Vicksburg, Miss., May 1965.

Smith, Travis, and Forsyth, Raymond, "Potrero Hill Slide and Correction," Journal of the ASCE, Soil Mechanics and Foundation Division, Vol. 97, No. SM3, March 1971, pp. 541-564.

South Dakota Highway Commission, Dynamic Tests on a Rolled Beam Composite Continuous Span Bridge, South Dakota Department of Highways Report, Part II, October 1955.

Stein, Stan, Traffic Flow Data Acquisition Using Magnetic Loop Vehicle Detectors.

Sullivan, B.R., Study of Vibration of Concrete, Report 2, Mechanical Impedance Measurements, Technical Report No. 6-780, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., August 1969.

Sutherland, H.B., "A Study of the Vibrations Produced in Structures by Heavy Vehicles," Highway Research Board Proceedings, Washington, D.C., 1950, pp. 406-419.

Swale, D.L., et al., "The Marconi/R.R.L. Vehicle Detector," Traffic Engineering and Control, Vol. 11, No. 6, October 1969, pp. 268-272.

Swift, G., and Moore, W.M., Investigation of the Applicability of Acoustic Pulse Velocity Measurements to Evaluation of Quality of Concrete in Bridge Decks, Texas Highway Department, Research Report 130-7, August 1971.

Switzer, G.G., Dynamics of Wheeled Vehicles, Report 4, A Statistical Analysis of Obstacle-Vehicle-Speed Systems, Technical Report No. M-68-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., March 1972.

Szendrei, M.E., A Comparison of the Field Performances of a Viatec Seismic Hammer Time Interval Meter (Model VH3), and N.I.R.R. Experimental Seismic Instrument (VH4), and an Haliburton Engineering Seismograph, Report No., RP/12/63, South African Council for Scientific and Industrial Research, National Institute for Road Research, Special Problems Division, Pretoria, South Africa, August 1963.

Tanis, F.J., Seismic Studies - Part 1: Seismic and Acoustic Data Processing for Determination of CPA and MR Vehicle Tracking Parameters, U.S. Army Mobility Equipment Research and Development Center, Final Report 1025006-F(1), March 1974.

Telluron, Development of a Prototype Miniature Magnetometer Vehicle Sensor, Report No. FHWA-RD-71-4, National Technical Information Service, Springfield, Va., November 1971.

Trott, J.J., and Grainger, J.W., Design of a Dynamic Weighbridge for Recording Vehicle Wheel Loads, RRL Report LR 219, Road Research Laboratory, Crawthorne, Berks., England, 1968.

Treiterer, Joseph, "Longitudinal Traffic Control by Infrared Sensing," Highway Research Record, No. 421, Highway Research Board, Washington, D.C., 1972, pp. 78-84.

U.S. Army Corps of Engineers, Deflections of Moving Tires, Report No 1., A Pilot Study on a 12 x 22.5 Tubeless Tire, Technical Report No. 3-516, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss. July 1959.

U.S. Army Corps of Engineers, Deflection of Moving Tires, Report No. 2, Tests with a 12.00 x 22.5 Tubeless Tire on Asphaltic Concrete, Sand, and Silt, 1959-1960, Technical Report No. 3-516, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., August 1961.

U.S. Army Corps of Engineers, Field Soniscope Tests of Concrete, Report No. 1, 1953 Tests, Technical Memorandum No. 6-383, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., April 1954.

U.S. Army Corps of Engineers, Field Soniscope Test of Concrete, Report No. 2, 1953-1957 Tests, Technical Memorandum No. 6-383, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss., March 1958.

University of Kentucky Research Foundation, Weighing Vehicles in Motion, Lexington, Ky., 1970.

Varney, Robert F., "Dynamic Interaction of Three-Axle Vehicle and a Two-Span, Partially Continuous Prestressed Concrete Bridge," Highway Research Record, No. 295, Highway Research Board, Washington, D.C., 1969, pp. 128-139.

VanDer Voort, A.W.M., A Speed and Acceleration Measuring System for Military Vehicles, Rapport PH. L. 1972-5 - ex. No. 17, Physisch Laboratorium RVO-TNO, Nederlandse Organisatie voor Toogepasi Natuurwetenschappelijk Ondorzoek ten behoeve van de Rijksverdediging, The Hague, Neth., January 1972.

Weiss, R.A., Detection Capability of a Strain Sensitive Cable Sensor, U.S. Army, WES Technical Report M-73-6, November 1973.

Whittemore, A.P., et al., Dynamic Pavement Loads of Heavy Highway Vehicles, Report No. 105, National Cooperative Highway Research Program, Washington, D.C., 1970.

Willey, William E., "Survey of Downhill Speeds of Trucks on Mountain Grades," Highway Research Board Proceedings, Washington, D.C., 1950, pp. 322-329.

Wilson, L.E., and Ravis, J.C., Development of a P/M Line Sensor, USAF, RADC Report TR-73-165, June 1973.

Wise, Joseph A., "Dynamics of Highway Bridges," Highway Research Board Proceedings, Washington, D.C., 1953, pp. 180-187.

Wright, D.T., and Green, R., Highway Bridge Vibration, Part II, Ontario Test Programme, Report No. 5, Ontario Joint Highway Research Programme, Queens University, Department of Civil Engineering, Kingston, Ont., Canada, 1963.

Ziolkowski, F.P., and Tsao, W.C.Y., "Antennas Buried in a Roadway for Vehicular Traffic Communications," IEEE Transactions on Vehicular Technology, Vol. VT-20, No. 4, November 1971, p. 104.

APPENDIX C

DETERMINATION OF BRIDGE COMPONENTS

Damping Factor - The formula employed to give an indication of the amount of damping present, by computing the average log decrements of amplitude for that portion of the trace that results after the test vehicle has left the test structure is:

$$ALD = \text{Log}_e \frac{A_o}{A_N} \times \frac{1}{n} ,$$

where

ALD = Average logarithmic decrement

A_o = Initial amplitude

A_N = n^{th} amplitude

n = Number of cycles.

Theoretical Natural Frequency - The theoretical natural frequency of a test structure is determined by considering the test structure as a single, continuous, uniform beam of homogeneous composition.

Since a bridge is actually constructed of steel and concrete, the relationship between the modulus of elasticity of steel and the modulus of concrete is generally set as 8.0.

The theoretically natural frequency may be determined from "Darnley's Frequency Equation" for the vibration of a three-span continuous beam of uniform cross-section,

$$f = F \left(\frac{I}{W}\right) ,$$

where

f = Theoretical natural frequency of vibration (cycle/sec)

F = Variable factor depending on span length ratio, etc. In this example (1), F = 0.645.

I = Total moment of inertia of superstructure cross-section

W = Weight per linear foot of superstructure (lb/ft).

For the test bridge example (1),

f = 2.73 cps

F = 0.645

I = 53,500 inches^4 (2,226,838 cm^4)

W = 2,993 lb/ft (4,454 kg/m)

$$f = 0.645 \quad \frac{53{,}500}{2{,}993}$$

f = 2.73 cps.

It was found, in this example and in most of the study results surveyed, that the measured natural frequency was from 5 to 10 percent higher than the theoretical value.

For the example given, the measured frequency was 2.9 cps (+6 percent).

Suspension Frequencies - The theoretically natural frequency of vibration for a vehicle suspension system is:

$$f_N = \frac{1}{2\pi} \quad \frac{K}{M} \ ,$$

where

f_N = Natural frequency

K = Spring modulus

M = Vehicle mass.

The spring modulus can also be shown as:

$$K = \frac{\text{load change}}{\text{deflection change}} \ .$$

At a near-loaded condition, the spring modulus for the following vehicle was determined as:

International Tractor:	K = 51,800 lb/inch (9,250 kg/cm)
Freuhauf Trailer:	K = 17,400 lb/inch (3,107 kg/cm)
Walter Truck:	K = 12,760 lb/inch (2,279 kg/cm)

The theoretical natural frequencies of the reference vehicle are then given for each of the above as follows for the International tractor:

$$f_N = \frac{1}{2\pi} \quad \frac{51{,}800 \times 12}{\frac{31{,}580}{32.2}} \qquad = 4.01 \text{ cps,}$$

for the Fruehauf trailer:

$$f_N = \frac{1}{2\pi} \quad \frac{17{,}400 \times 12}{\frac{31{,}900}{32.2}} \qquad = 2.31 \text{ cps,}$$

for the Walters truck:

$$f_N = \frac{1}{2\pi} \quad \frac{112{,}760 \times 12}{\frac{\pm 7{,}840}{32.2}} \qquad = 2.65 \text{ cps.}$$

There are interesting results here in the spread of natural frequency between the load condition of the tractor (4.01 cps) and trailer (2.3 cps). Generally, in the past, the suspension frequency was assumed to be at the higher tractor rate (approximately 4 cps).

<u>Critical Velocity</u> - Considering the natural frequency of vibration of the test structure (1) and the distance between the vehicle's wheels (axle spacing), critical velocities can be determined for each vehicle. The critical velocity is the velocity that produces successive wheel impacts that match the natural frequency of the structure:

V_c = Critical velocity

$V_c = d \times f,$

where

d = Distance between axle or axle sets

f = Actual natural frequency of vibration of the structure.

From the tractor-trailer combination (3S2), the critical velocity for the various axle combinations are:

V_{c_1} = Distance between driver trailer axles:

V_{c_1} = 4 x 2.9 cps = 11.6 ft/sec (3.54 m/sec) [approximately 8 mph (12.87 km/hr)]

V_{c_2} = Distance between front wheels and tandem sets:

V_{c_2} = 13.2 x 2.9 cps = 38.3 ft/sec (11.67 m/sec) [26 mph (41.84 km/hr)]

V_{c_3} = Distance between driver tandem set and trailer tandem set:

V_{c_3} = 20.7 x 2.9 cps = 60.0 ft/sec (18.29 m/sec) [65.98 km/hr)]

For vehicle (B), Walters truck:

V_c = 11.5 x 2.9 cps = 33.4 ft/sec (10.18 m/sec) [approximately 24 mph (38.62 km/hr)]

The effect of critical velocity is demonstrated in the reference, where the measured dynamic load was 129 percent of the static load at a velocity of 47.23 ft/sec (14.4 m/sec) [32 mph (51.5 km/hr)] using the tractor trailer.

The critical velocities for the tractor trailer are 8, 26, and 41 mph (12.87, 41.84, and 65.98 km/hr). Comparing these with the critical velocities shown in the referenced study (1), it is seen that:

1. The 32 mph (51.5 km/hr) velocity fell between the 26 mph (41.84 km/hr) and 41 mph (65.98 km/hr) of the long wheel bases, but fell on the fourth (4x) harmonic of the tandem.

2. A probable worst case would be at 41 mph (65.98 km/hr), where a primary critical is shown and the heavily loaded axle set.

3. The fifth (5x) harmonic of the tandem set [8 mph (12.87 km/hr)], also heavily loaded.

REFERENCES

(1) South Dakota Highway Commission, Dynamic Tests on a Rolled Beam Composite Continuous Span Bridge, South Dakota Department of Highways Report, Part II, October 1955.

(2) Nasser I. Al-Rashid, Clyde E. Lee, and William P. Dawkins, A Theoretical and Experimental Study of Dynamic Highway Loading, Report No. 108-IF, University of Texas, Center for Highway Research, Austin, Texas, 1972.

APPENDIX D

CONCEPTUAL SEISMIC SENSOR SYSTEM

Seismic sensors and the strain gages appear to be the only potentially practical indirect forms of dynamic load sensors. Since this study did not include strain gages in its investigation, the seismic sensor, i.e., seismometer and geophone, was the only probable indirect form investigated. As was indicated in the basic study report, all information regarding the feasibility of using seismic sensors to acquire indirect dynamic axle load data was favorable, but inconclusive. The major difficulties arise in the identification of the components acquired from a dynamically loaded bridge deck and in establishing a practical and valid relationship to the axle loads.

It should be noted that the primary stimulus for investigating a beneath-the-deck PVD was due to an attempt to determine if a total sensor package could be developed, based on using a seismic sensor, that was installable beneath a bridge deck. If conclusive evidence had been established which justified the use of a seismic sensor, the combination of a seismic sensor and the PVD, recommended in the basic report, would have provided an extremely desirable sensor package. It would only require installation beneath the deck under the lane to be sampled. The LPP and the master processing hardware, with the sensor package, i.e., the entire system, would be very nicely installable under the bridge. The concept may, in fact, be feasible, and might be proven so with some test and evaluation effort.

The major problem area, as implied above, arises in the off-line data-reduction process, not in the acquisition and recording hardware. The hardware system suggested in the basic report is also useable with a seismic sensor array.

The seismic sensors and their interface hardware would basically replace the direct-contact sensor array and its interface hardware. Some small modifications appear necessary for the axle load threshold test in the on-site processing hardware. Consequently, a discussion of the data-reduction process is presented below.

Reduction of the Seismometer - PVD System Data

The requirements for off-line reduction of the data acquired from the seismometer PVD system are quite significant and complex. The seismic signals generated by each wheel of the vehicle from the time that the front axle wheels contact the span which has been instrumented to the time that the bridge has damped out its excitation are contained in the signal. This signal should behave in a manner similar to the composite dynamic load function of the vehicle, i.e., composed of all of the wheel dynamic functions. However, the seismic signal tends to rise and fall exponentially about the seismic value measured at a point nearest to the seismometer, i.e., as the vehicle draws near to the sensor and as it pulls away from the sensor.

Further, any given seismic sensor will acquire, again as a composite signal, a signal containing all of the vehicles on the span simultaneously, i.e., within the appropriate lagged times. As a result, the segregation of a multiple vehicle seismic signal and the generation of the related force-time data at each wheel during passage over the span necessitates a very complex process which requires significant off-line computer capability. This implies that the

discarding of load data for vehicles with axle loads of under 2,000 lb (907 kg) can only be accomplished with minimum on-site hardware, on the basis of calibration data for the given bridge. Otherwise, it can only be accomplished by off-line computer processing.

<u>Seismic Precalibration of the Bridge Deck</u> - The compression, shear, and Rayleigh wave velocities must be determined for the bridge span to be instrumented in advance of reduction. The thickness of the concrete, as a function of longitudinal and lateral position, must also be determined. If there is any chance that a layering effect exists, such as delamination, then each layer must be calibrated seismically. Acoustic or refractive seismic techniques may be used for this purpose. If an asphaltic concrete surface has been laid over the concrete deck, then both the asphalt and the concrete layers must be calibrated.

Road roughness must be characterized and can be acquired by a profilometer. Since road roughness effects appear, from several investigations, to provide the highest frequency component in the dynamic load function generated at the wheel-deck contact points, and since seismic investigations relate road roughness with Rayleigh wave behavior, the calibration of road roughness of the bridge deck would be of value in reducing the acquired dynamic data. A profilometer could be used to acquire the raw road roughness data. Subsequent reduction of this data to determine amplitudes, frequencies, and wavelengths and heights would provide a basis for predicting frequencies and amplitudes which would be present in the dynamic load function of a wheel; e.g., one investigation (1) reduced frequencies and amplitudes per

linear foot of travel, i.e., cpf and apf. Given the vehicle speed, the frequency in the time domain is simply:

$$fcps = \frac{fcpf}{Vfps} .$$

This frequency value can be used to either filter out the road roughness contribution in an acquired signal or to identify it. In the case of seismic signals, it can be input to the wave propagation model to determine the Rayleigh wave contribution.

If the deck of the bridge exhibits varying seismic properties, i.e., through its length, width, and depth, a map of these properties should be constructed during calibration of the deck for use in the data-reduction process.

If a bridge deck shows any significant variation in its seismic (or microwave) properties because of meteorological effects, the seismic properties for each meteorological state should be calibrated prior to reducing any of the acquired data, e.g., saturated from rain, covered with snow, partial saturation, etc.

<u>Input Data from the Seismometer-PVD System</u>. It is assumed that the roadside seismic-PVD signal processor will:

1. Filter as much noise from all signals as possible

2. Insert time

3. Perform whatever signal separation possible

4. Record all sensors, in parallel, digitally, e.g., for a three-lane bridge, three PVD signals, six seismometers (two per lane), and a timing signal. Each microwave data set would contain, e.g.:

   a. Vehicle entry indicator (1 bit)

   b. Axle passage indicator (1 bit)

   c. Vehicle exit indicator (1 bit)

   d. Doppler speed of vehicle (6 bits)

   e. PVD number would be implied in the order of the recording. The sensor number would also represent the lane number.

   Provision for at least four PVD's should be made to allow operation on a four-lane bridge.

5. The seismic data set should contain:

   a. Amplitude of signal (7 bits)

   b. Seismometer sensor number will be implied in the order of the recording.

   Similarly, provision for a maximum of eight seismometers should be made, two per lane.

6. The total data record per time point should be as follows:

a. Time

b. PVD record (repeated)

1
(1) Vehicle entry indicator (1 bit)
(2) Axle passage indicator (1 bit)
(3) Vehicle exit indicator (1 bit)
(4) Doppler speed (6 bits)

.
.
.

n
(1) Vehicle entry indicator (1 bit)
(2) Axle passage indicator (1 bit)
(3) Vehicle exit indicator (1 bit)
(4) Doppler speed (6 bits)

where

$2 \leq n \leq 4$.

c. Seismic record (repeated)

(1) Amplitude of 1st seismometer or geophone (7 bits)

.
.
.

(n) Amplitude of nth seismometer or geophone (7 bits)

.
.
.

where

$$2 \leq n \leq 4.$$

The presence of "1" in an indicator position implies existence of the event. A "0" implies that either a null condition exists or the previous indicator is still in effect.

It would be desirable if significant meteorological effects would be automatically recorded, e.g., the existence of rain over a sufficiently long period to cause a change in bridge deck seismic parameters. This would be necessary for unattended automatic operation of the system. This would also require another sensor and another variable to be recorded, i.e., a 1-bit rain indicator, as a function of time, an indicator for snow, etc.

Since the frequency of interest, the fundamental truck frequency, is on the order of 3-4 cps, and a good representation of a cycle of the function can be determined with eight sample points, a maximum sample interval of 1/32 sec, or 2^{-5} sec, is necessary. If a good representation of the higher order functions is found necessary, this interval must be proportionately decreased in size. Since road roughness is the highest frequency driving function normally encountered, and since it is on the order of 40 cps, a lower limit of the sampling interval appears to be 1/512 sec, or 2^{-9} sec.

Reduction Process for the Seismometer-Microwave Data

The reduction process necessary to reduce the acquired seismic-microwave data is illustrated in Figure 36. The functions defined in the flow chart are all self-explanatory. However, in a few instances, the total functions performed are not evident and require additional explanation. In the selection of the bridge deck calibration data necessary to the conversion of the acquired data, or to, in general, the reduction process, variability in the parameters due to external environment factors, such as rain, snow, etc., must be allowed. A tabular set of each parameter which varies, as a function of the environmental factor, should be included such that, if the environmental state is defined, as an input, the proper set of parameters can be selected for use during a given processing.

The establishment of the position time history of each axle, and, hence, each wheel, is necessary to the reduction of the seismic signals. Since each wheel, at a given time, is a

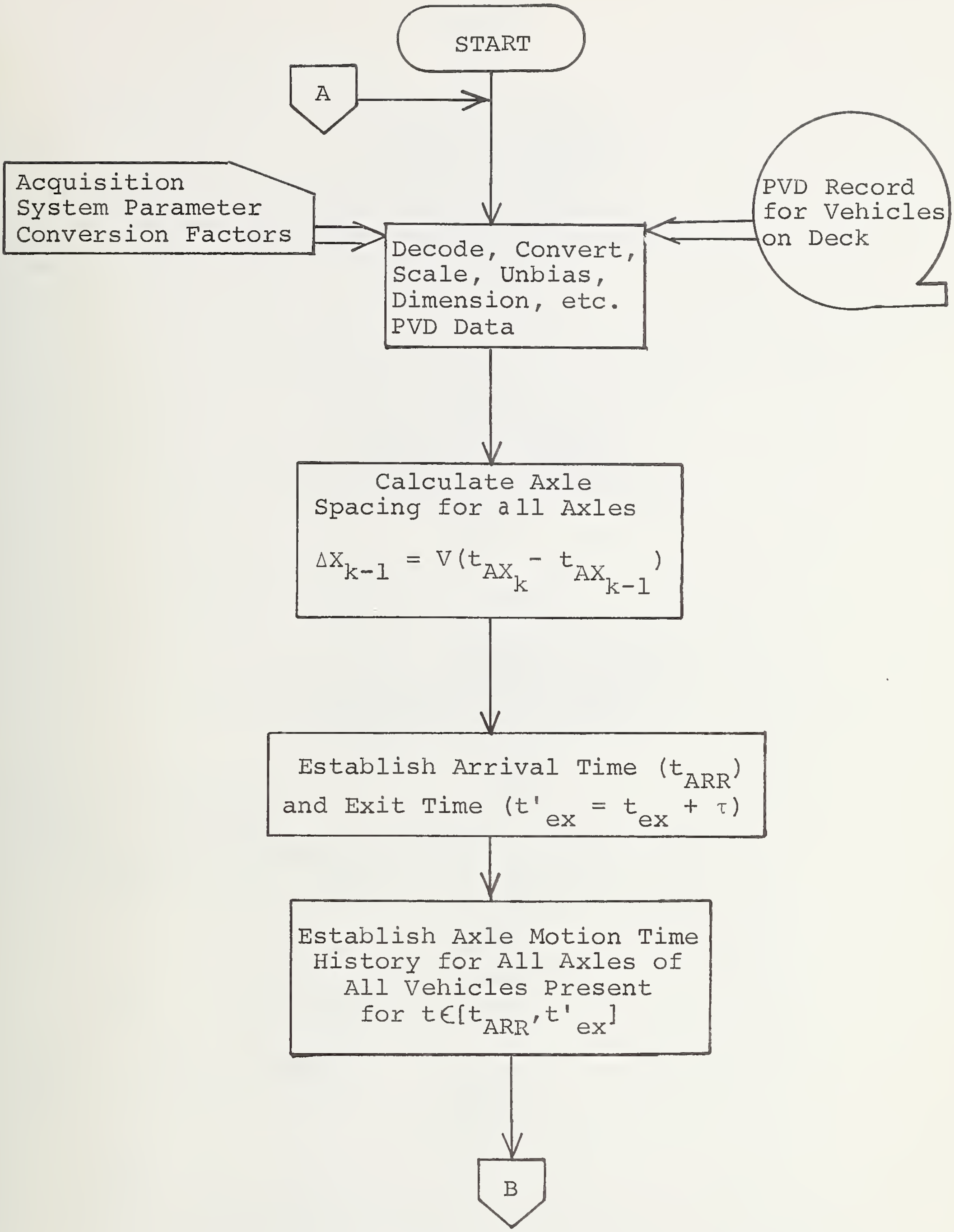


Figure 36. Seismic data reduction process.

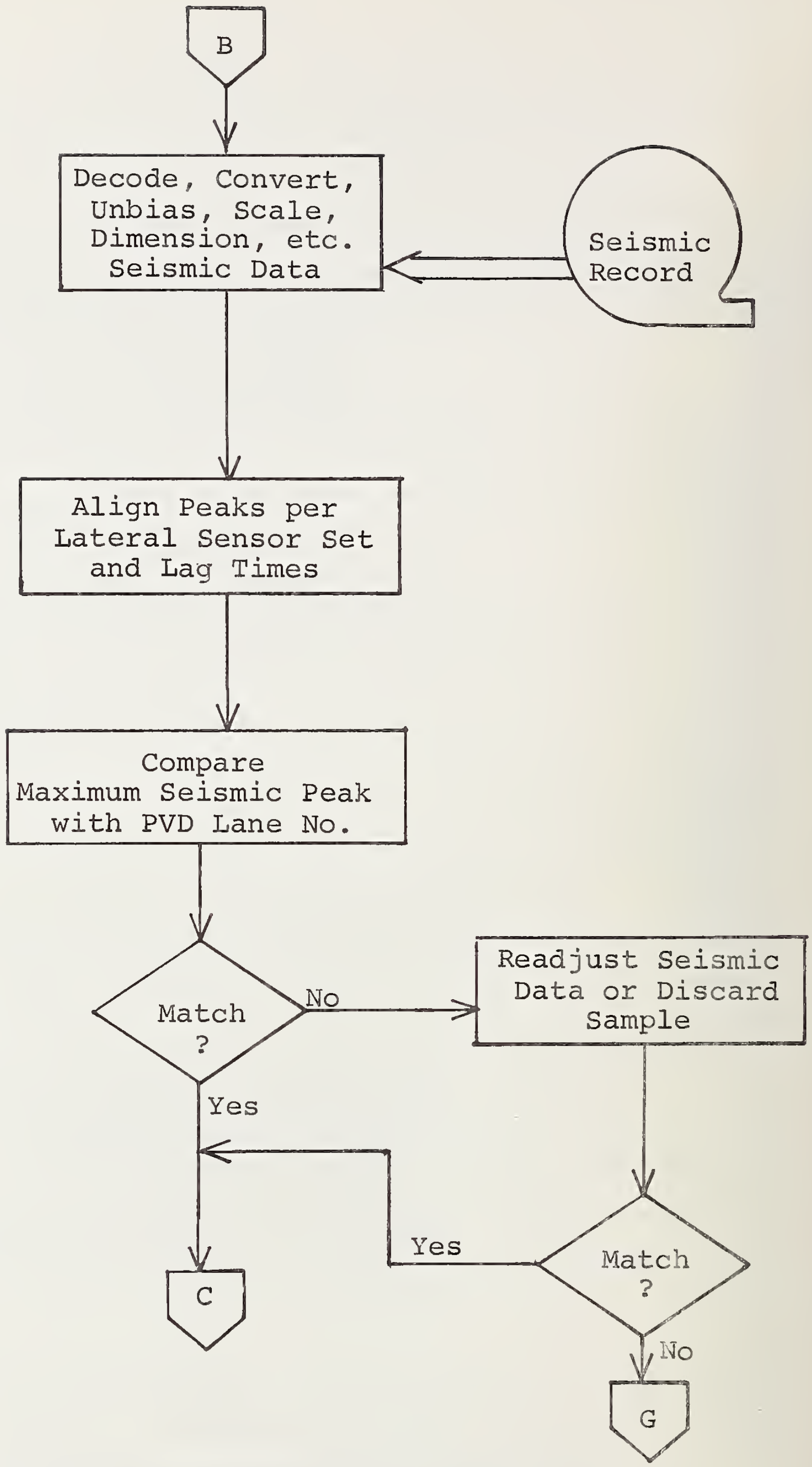
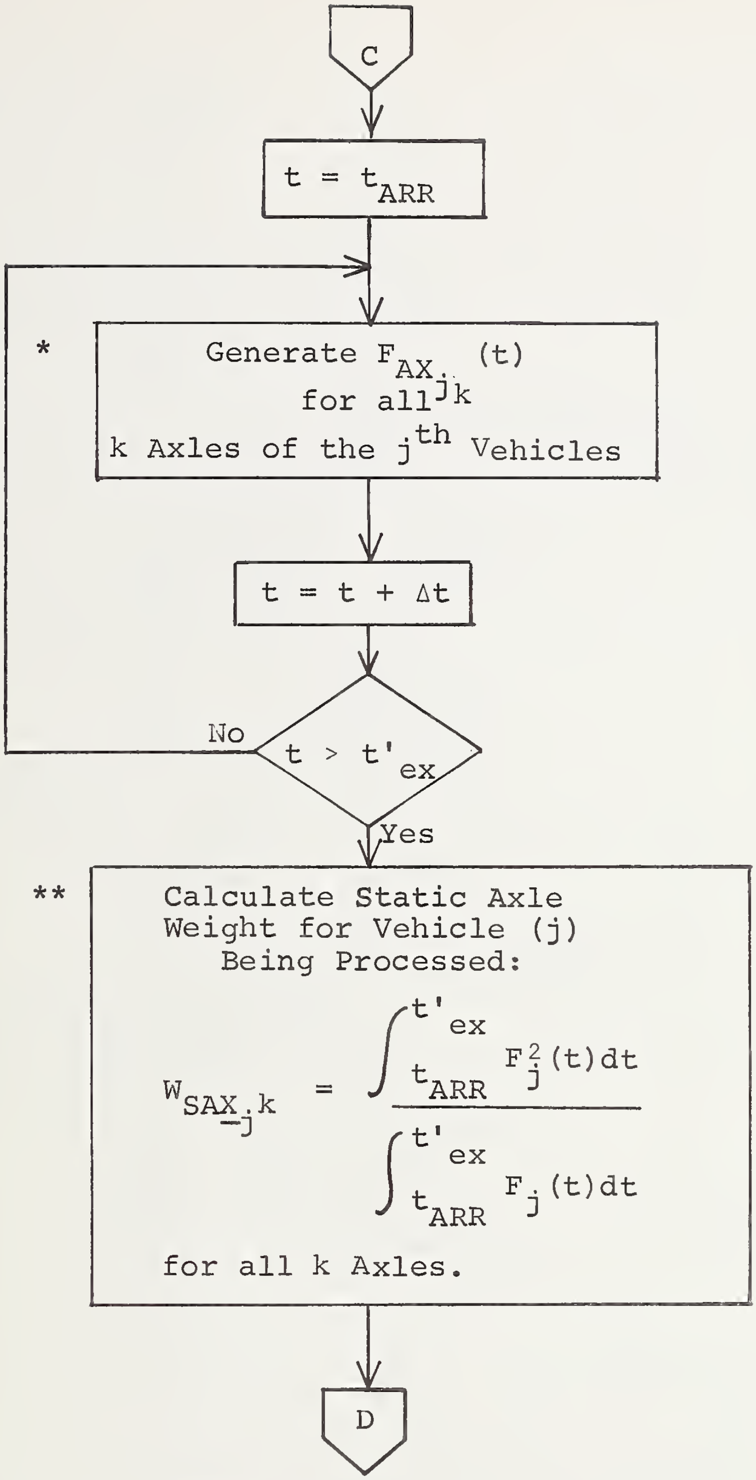


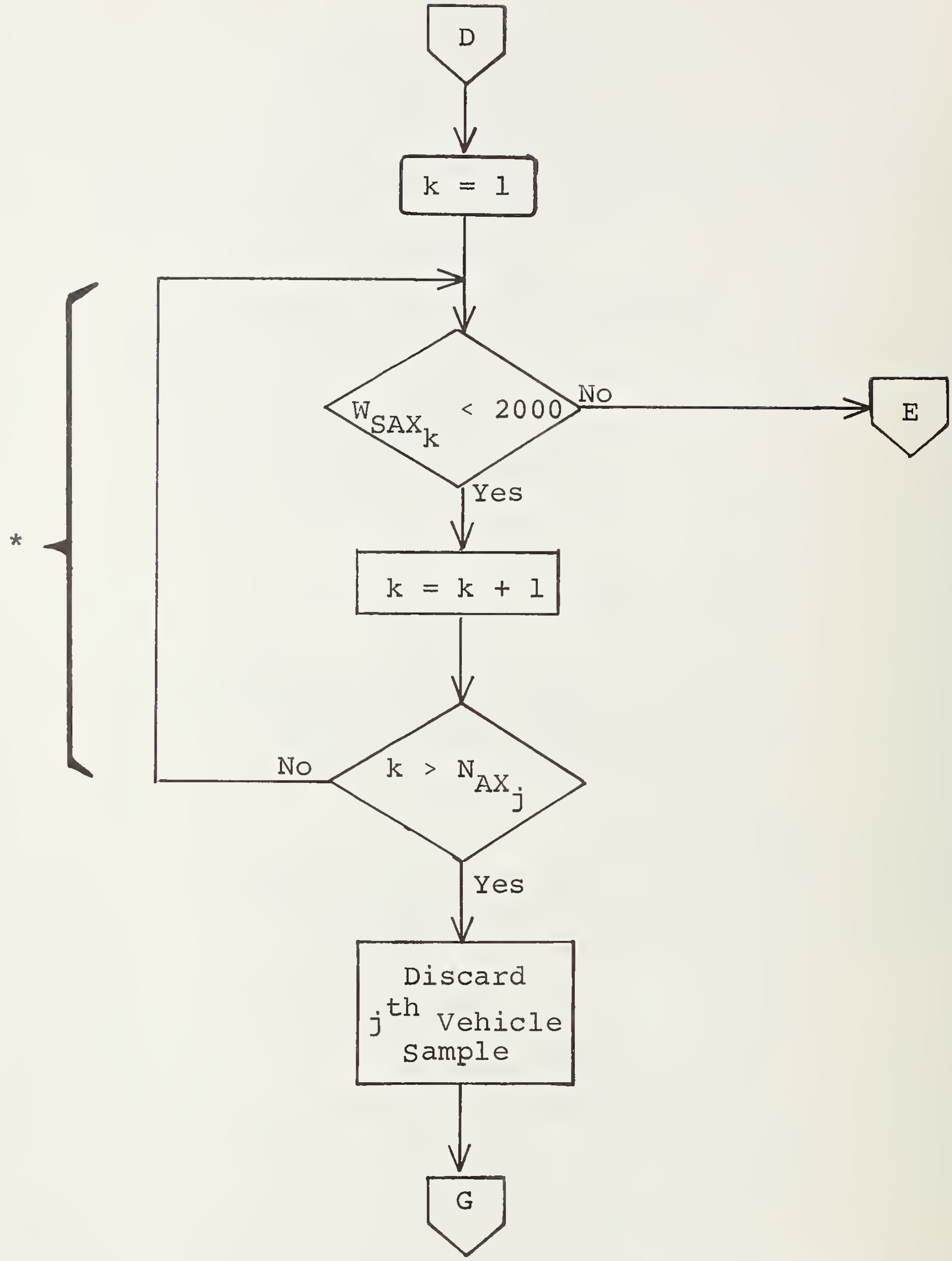
Figure 36. Seismic data reduction process (Continued).



* Unresolved process

** Herricks Method or RMS can be used as alternates.

Figure 36. Seismic data reduction process (Continued).



* This operation can be deleted if on-site processing hardware performs this test in real time.

Figure 36. Seismic data reduction process (Continued).

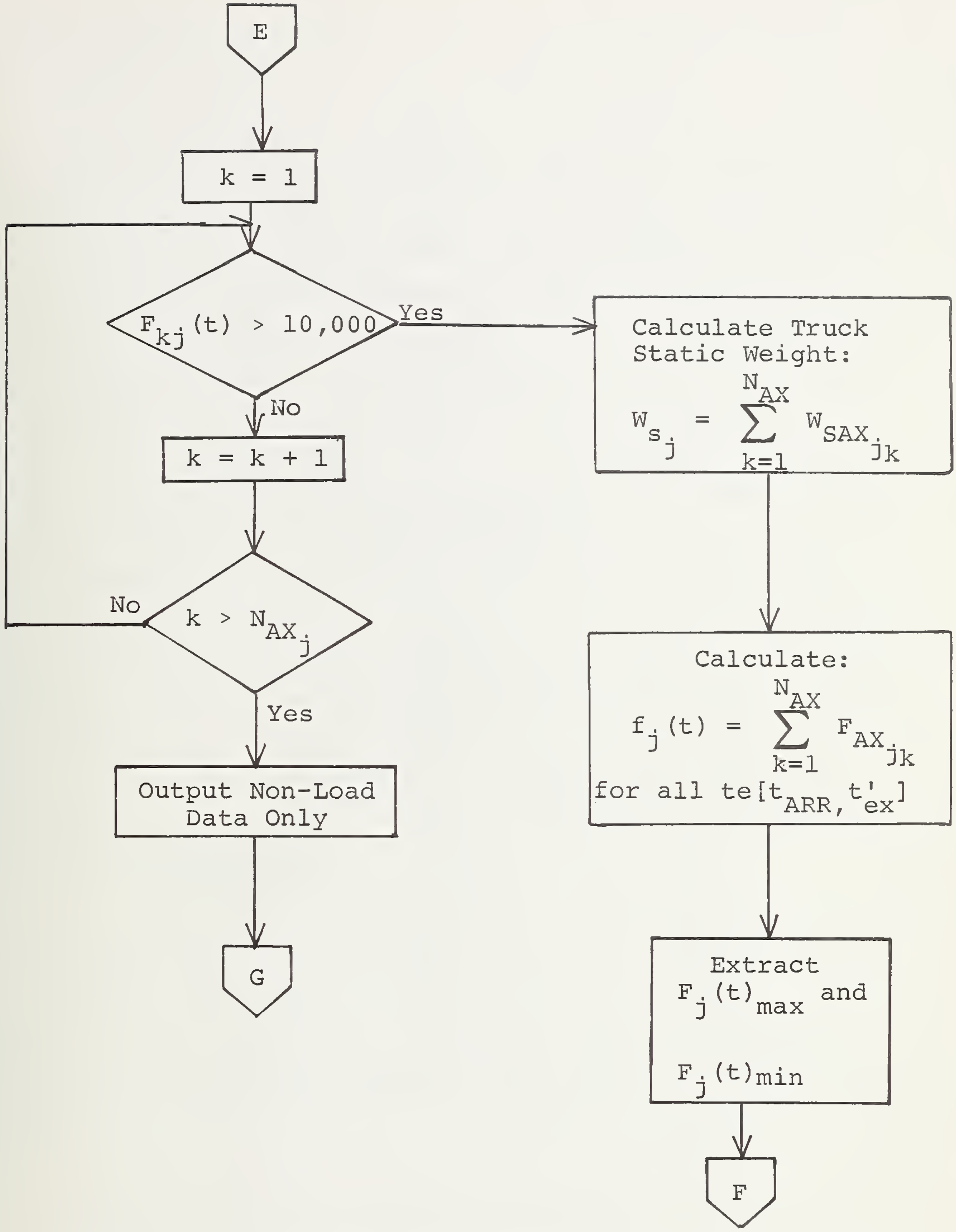


Figure 36. Seismic data reduction process (Continued).

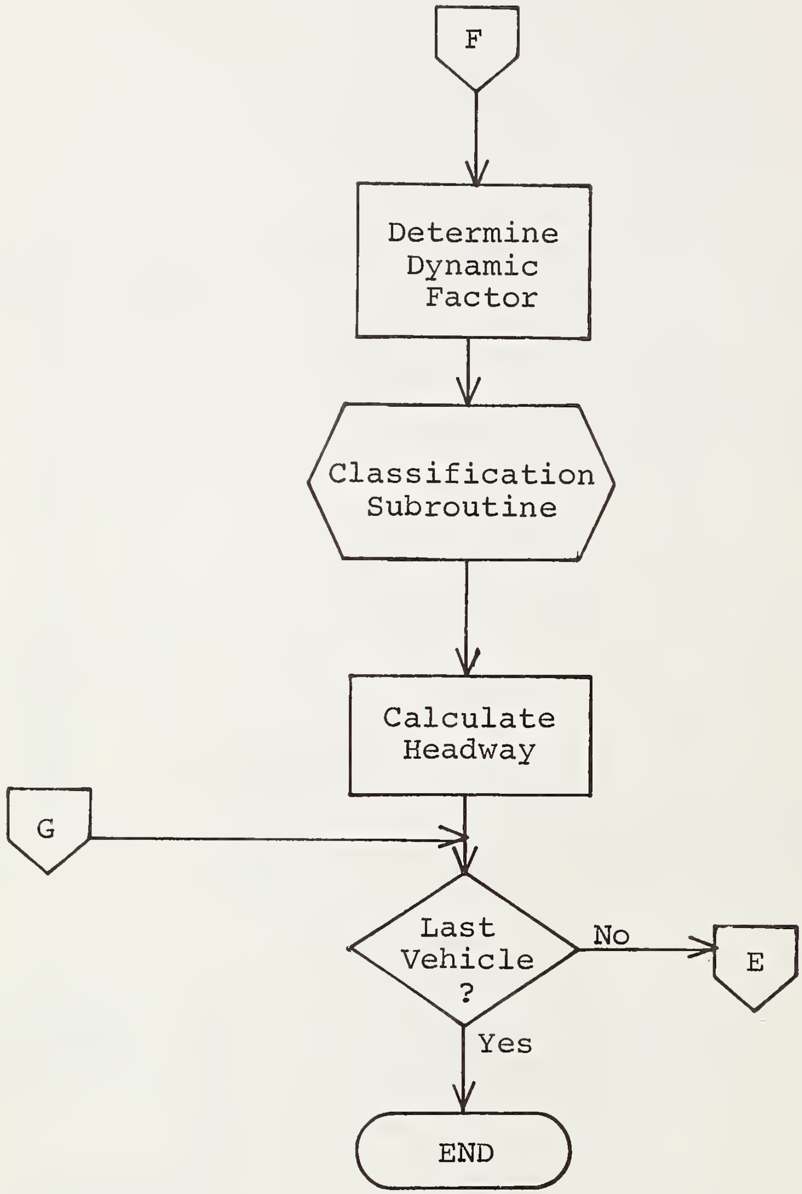


Figure 36. Seismic data reduction process (Continued).

seismic energy source, the position of each wheel at the given time locates the seismic energy sources.

The function shown in the flow chart (Figure 36) to align the peaks, as a function of lagged time, is to ensure the matching of the seismic and microwave signals. The matching is based on the fact that the seismic signal reaches its maximum amplitude at the point where the energy source trajectory is nearest to the sensor. Since each lateral set in the seismometer array lies on a line normal to the longitudinal axis of the span, when the energy source (wheel) lies on this same line, it is at its nearest point to each seismometer. The amplitude at each sensor is then of the distance to the energy source. The absolute maximum peak measurement of the set measured at the instant of alignment, adjusted for lag time, will indicate the nearest seismometer, if they are adequately calibrated, which also indicates the lane of occupancy. Since the microwave sensor number also identifies the lane of occupancy, a verification of the lane of occupancy can be made, as well as verification of vehicle identification within the seismic data by peak matching.

The received seismic energy is generated as a function of the dynamic load function seen by the bridge deck at the contact point(s) between the tire(s) and the deck. This dynamic load function is composed of several components, each with a different frequency ranging from 0 to 40 cps, e.g.,

$$F(t) = f\,\{g,\ (v,t,w_s),\ g_2(v,t,w_s),\ \ldots\}\ .$$

In the reduction process, the objective is to determine F(t), i.e., the resultant vehicle dynamic load function which is imposing on the bridge. The determination of the subsidiary function is of no real consequence to this work. However, the resultant dynamic function at each wheel is of consequence and is used to derive the total axle and, subsequently, the total vehicle dynamic function.

It would appear that, in order to adequately recover and represent the force time function of a given source, i.e., a wheel or dual wheels, all components of the seismic signal must be recovered, including the surface waves. The only portion of the force-time function that appears to be missing is that which contributes to the motion of the bridge deck. The seismic recovery would also include all rebounding, refractive waves. However, if certain assumptions are made concerning a single wave component and the behavior of the energy sources, i.e., that the other components of the total seismic signal exist and are proportional to the observed component, and a calibration of that component as a function of location, speed, and load is made, that wave component, assuming that the dominant wave is selected, could be utilized singly. In this case, all other wave forms should be filtered from the seismic signal.

In the seismic reduction problem, we are given the measured seismic signals at several specific locations on the bridge deck. We can identify specific waves and separate them, e.g., compression wave, horizontal and/or vertical component, shear wave, horizontal and/or vertical, Rayleigh wave, etc. We are also given the location of every energy source on the deck at any given time. Further, we know the forward

speed of each vehicle and, consequently, of each wheel, and its rotational speed. We can also make estimates of the frequencies of vibration of the wheel from this data. However, we do not know what the applied mass is at each of these source locations. We also know the seismic characteristics of the bridge deck and its surface roughness profile. From this information, we must work inversely along the propagation path to each source location and define the force-time function applied at each source point for each instant of time.

The most straightforward solution is to seismically calibrate the bridge deck according to dynamic loads. However, this still leaves the distinguishing and identifying problem unresolved for the case of multiple vehicles. Certain characteristics can be established from the microwave data, which will allow at least some separation of the received seismic signals. Since seismic signals vary in persistence as a function of the size of the vehicle, even though a smaller vehicle may have the same peak amplitude, at a different spatial location, than a larger vehicle, its signal duration is less. This criterion can be applied to the signal separation problem. Also, some experimental evidence exists which indicates that good vehicle lanal definition exists in the seismic signals. This evidence also implies that discernment between vehicles is possible longitudinally.

An alternate approach that warrants investigation is an energy equilibrium method; i.e., given the attenuation properties of the transmission media, its transmission properties, the source location, and the total delivered wave energy, demonstrated by particle velocity, the input energy

can be estimated, and, presumably, the input force-time function at the source. This approach is extremely sophisticated and complex. Further, substantial research work must be performed before this method can be applied practically.

Another approach exists which is based on the use of the inverse propagation model. Propagation models have been developed which, given the source functions and transmission media characteristics, will generate the seismic signal at the receiver. This implies the feasibility of the inverse; i.e., given the seismic signal at one or more receivers, the media characteristics, location of the sources, as a function of time, the model of the propagation process between the source, and the receiver, the source input functions, F(t), can be determined.

A model which has been used with some success (2) (see Figure 37) is fundamentally defined as:

$$\dot{q}_{\ell}(r,t) = \sum_{j} e^{iw_j t} A_{jm} B_{mj\ell}(k_{m,j}, S) C_{m,j}(k_{m,j}, S)$$

$$H^{(1)}_{\ell-1}(k_{m,k} k_r),$$

where

ℓ	=	1... Vertical Component 2... Horizontal Component
j	=	1,2,..., a... frequencies
m	=	1,2,..., b... mode number

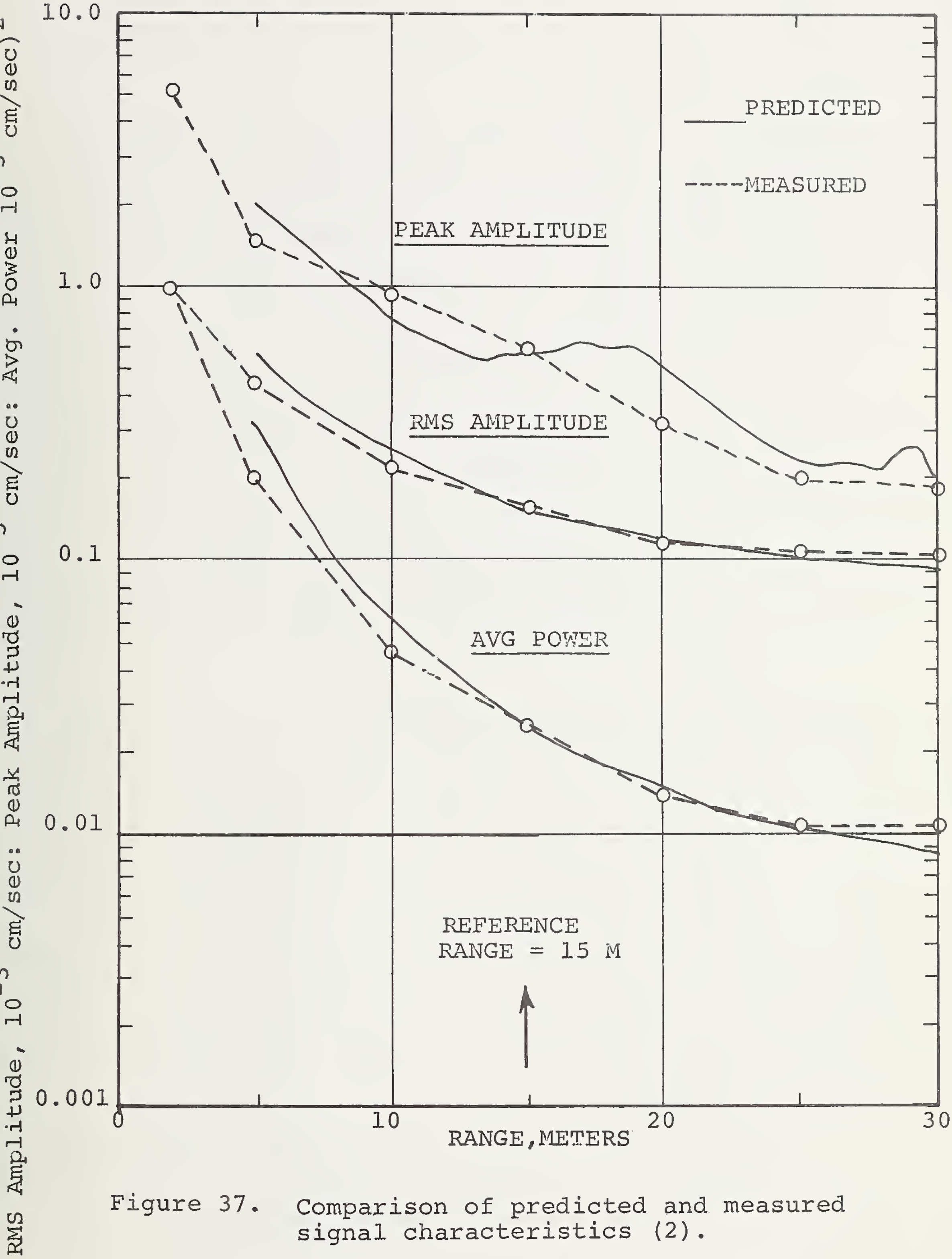


Figure 37. Comparison of predicted and measured signal characteristics (2).

r = ... radial distance

t = ... time

A_j = ... frequency component of source

$B_{m,j,\ell}$ = ... coefficient of layered media

$C_{m,j}$ = ... coefficient for surface geometry

$k_{m,}(S) = \frac{2\Pi}{\lambda_{m,j}}$ ... wave number

S = ... media parameter

$H^{(1)}_{\ell-1}(k_{m,j}r)$ = Hankel - function of the first kind and order $\ell-1$

$$= \sqrt{\frac{2}{\Pi_{k_{m,j}}r}} \, e^{ik_{m,j} r_j - \ell - .5} \text{ for } K_{m,j} r >> 1.$$

Particle velocity, $\dot{q}$, has vertical and horizontal components, identified by ℓ, and is a function of the distance, r, and time, t. It is expressed in the general form of the model as the product of the sum over all frequency components, j, and the exponential time dependencies. The amplitudes for each frequency of the various possible modes, m, must be added. The Hankel function relates the signal characteristics (dependency) on the distance, r, and the wave numbers, k_m. The wave number for the various modes, m, are determined from dispersion relations. Effects due to layer thickness and number of layers on seismic wave amplitudes are included in the B factor. The C factor is used to modify the wave amplitudes caused by macrosurface geometry variations, and A factors are the frequency components of the source.

A simple approach would be the use of multiple seismometers in an array, sufficient to establish a set of independent simultaneous equations to determine the forces being applied at each source point. Assuming a single source for each set of dual wheels and each single wheel, a prohibitively large quantity of seismometers is created; e.g., on a two-lane, 100-ft (30.48-m) span there could be from about 24 to about 40 sources. However, extending the peak matching concept to a longitudinal-lateral array of a lateral three-seismometer set located at 20- to 30-ft (6.1-m to 9.1-m) intervals in the longitudinal direction would provide a means to match peak amplitudes at a given time, with known source locations, in both directions, and still maintain a lag time of some significance between seismometers. This approach may be the most practical method of deriving the force-time function of a set of wheels existing simultaneously on a deck. However, a dynamic load calibration of the instrumented deck would further simplify this process, as opposed to using the inverse propagation model.

REFERENCES

(1) A.N. Brinkman, J.C. Wambold, and J.R. Zimmerman, "An Amplitude Frequency Description of Road Roughness," Improving Pavement and Bridge Deck Performance, Special Report 116, Highway Research Board, Washington, D.C., 1971, pp. 53-67.

(2) L.E. Link, Jr., and W.F. Marcuson, III, Mapping Seismic Response Characteristics of Complex Terrain, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss., 1972.

FHWA

R&D